PHOTO VOLTAICS AND MUNICIPAL SOLID WASTE AS DISTRIBUTED GENERATION RESOURCES: MODELING, ANALYSIS AND BENEFIT QUANTIFICATION

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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DECLARATION

I hereby declare that the Research Thesis entitled, "**PHOTO VOLTAICS AND MUNICIPAL SOLID WASTE AS DISTRIBUTED GENERATION RESOURCES: MODELING, ANALYSIS AND BENEFIT QUANTIFICATION**", which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfillment of the requirements for the award of the **Degree of Doctor of Philosophy** in **Electrical and Electronics Engineering**, is a bonafide report of the research work carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to certify the Research Thesis entitled "**PHOTO VOLTAICS AND MUNICIPAL SOLID WASTE AS DISTRIBUTED GENERATION RESOURCES:MODELING, ANALYSIS AND BENEFIT QUANTIFICATION**" submitted by Mr. **S.B.Karajgi (Register No.040330EE04P5)** as the record of the research work carried out by him, is accepted as the Research Thesis submission in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy

Prof. Udaykumar. R.Y
(Research Guide)

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(Signature with date and Seal)

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ABSTRACT

The modified quantification of some of the benefits of the Distributed Generation (DG), is proposed in this investigation. Two indices – System Loss Reduction Index (SLRI), and Voltage Regulation Ratio (VRR) are quantified and proposed. In addition, other issues like fault location and the kVA delivered by the substation are also analyzed with the inclusion of DG.

Two resources are considered for DG. The PV solar energy is modeled using the probabilistic approach with the cloud cover as the random variable. Beta distribution is employed in the investigation. The energy generated by incinerating the Municipal Solid Waste, is selected as the second resource. This energy is modeled in terms of the waste flow paths and mass balance equations are analyzed. For both the resources, economic considerations are also carried out.

To quantify the benefits of DG, a practical distribution system is simulated and both the DG resources are incorporated in the system. The two indices are obtained as a ratio of the corresponding quantity with and without the inclusion of DG with same loads. To analyze the effect of DG on the location of fault, a single line to ground fault is simulated on both the HV side and LV side and the location of the fault is obtained with and without the DG in the system. Similarly, the effect of DG on the kVA delivered by the substation is also analyzed by varying the operating power factor of the DG.

With the inclusion of DG, the simulation results indicate that the system loss decreases and the voltage profile improves. However, this depends on the DG rating and the indices show a reverse trend as DG rating go up. As expected, the error in the location of fault increases with the rating of DG. The simulation results clearly show that the faults occurring on the low voltage side of the distribution system are not likely to be detected at the substation end and this becomes more significant with the inclusion of DG. On the contrary to the normal understanding that DG reduces the power demand on the substation, it is observed from the simulation that the kVA delivered by the substation is not reduced to a greater extent if the DG is not capable of supplying the reactive power demand.

Key Words : System Loss Reduction Index (SLRI), Voltage Regulation Ratio(VRR), Municipal Solid Waste. (MSW), Incineration.

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NOMENCLATURE

A,B,C,D	Line constants
A_{pv}	Effective area of the solar cell, m2
A_W	Ash content of the waste, %
B_r	Susceptance of the load at node 'r', mho
B_{xy}, C_{xy}	Line constants between x and y
CostU	Cost function to be minimized, Rs
CVn	Calorific value of nth component of the waste, kcal/kg
$CVoverall$	Calorific value of the sample, kcal/kg
C_W	Combustible content of the waste, %
e	Electric charge, Coulomb
$f_{kj}(k_j)$	Probability function for cloud cover
$f_{po,j}(p_{o,j})$	Probability distribution function for PV output
Gr	Conductance of the load at node 'r', mho
I_{0f}, I_{1f}, I_{2f}	zero, positive and negative sequence currents at the fault F
I_{am}	current flowing through the faulty line from m to the network, Ampere
I_G	Current delivered by DG, Ampere
I_i	current flowing through i^{th} segment (Ampere)
i_j	Insolation during j^{th} time interval, KW/m^2
$I_{L,PV}$	Load current output of Solar Cell, Ampere
$I_{max,j}$	maximum insolation during j^{th} hour of daylight, KW/m^2
$I_{O,PV}$	Saturation current of solar cell, Ampere

$I_{S,PV}$	Current in the solar cell, Ampere
k	Boltzman's constant
K_a - K_w	Complex parameters
K_i	Weighting factor for the bus.
k_j	Random variable representing j^{th} hour cloud cover
K_{Loss}	Loss factor
Kp	Packing factor of the solar cell
l_i	length of i^{th} segment, meter
LLRI	Line Loss Reduction Index
Mn	Weight of the nth component of waste on dry basis, Ton
Mwaste	Total waste collected, tons/day
N	Number of buses
P_{C_i}	core loss of i^{th} transformer, Watts.
P_{LV_i}	Losses on the low voltage side of the i^{th} transformer, Watts.
$P_{max,j}$	Maximum solar output during jth hour under clear sky conditions, KW
$P_{O,j}$	Solar output during jth hour, KW
r	Line resistance, ohms/meter
R_f	fault resistance, Ohms
s	Per unit distance of the fault point from the starting node of the section, meter
SLRI	System Loss Reduction Index
T	Temperature in ^{O} Kelvin
V	Voltage, Volt
V_{am}	Phase voltage of the faulty phase at node m, Volt

V_{of}, V_{1f}, V_{2f}	zero, positive and negative sequence voltages at the Fault F
VP	Voltage Profile
VPII	Voltage Profile Improvement Index
V_{PV}	Voltage across the junction of solar cell
VR	Voltage Regulation
VRR	Voltage Regulation Ratio
W_W	Moisture content of the waste, %
x(An)	Weight of the waste that follows path An, tons
x_{0ab}	Zero sequence reactance of the line between nodes ‘a’ and ‘b’, ohm
x_{1ab}	Positive sequence reactance of the line between nodes ‘a’ and ‘b’, ohm
x_{2ab}	Negative sequence reactance of the line between nodes ‘a’ and ‘b’, ohm
x_{ab}	Reactance of the line between nodes ‘a’ and ‘b’, ohm
$X_{u,k}$	mass of waste item ‘k’ processed by unit process u, tons/year
Y	Admittance, mho
Z_{app}	Apparent Impedance, ohm
α_j	Scale parameter of beta distribution
$\alpha_{u,k}$	cost coefficient for processing waste item ‘k’ at unit the process ‘u’ in Rs./ton.
β_j	Shape parameter of beta distribution
η	Efficiency
σ	Standard deviation of the cloud cover
$\tau (x)$	Gama function

μ	Mean of the cloud cover
Y_I	Sub Matrix of admittance Matrix

CHAPTER 1.

INTRODUCTION

1.1 Distributed Generation:-

Electrical energy is the most important form of energy that people need every day, no matter when and where they are. In the recent past, high technology sectors as well as the traditional industrial sectors have seen a high degree of improvements in productivity. These improvements, in conjunction with, the changing lifestyle of mankind, have resulted into inventions of a number of equipment, machinery and instruments that have posed a great demand for electricity, which may increase exponentially in the future. On the contrary, the pace at which the production of electricity is increasing has not been so satisfactory. In developing countries like India, the situation is quite alarming because of the scarcity of the fuel required for the electrical power generation. Any effort in enhancing the energy production through large hydro OR thermal OR nuclear stations, have been futile because of the growing concern about the environmental hazards caused by these units. The world energy scenario is not much different. During this period of time, the concept of Distributed Generation (DG) was introduced [Bayegan. M, 2001]. Within no time, DG created a sensational interest amongst all those who are involved with power distribution.

DG can be defined as the small power generation, ranging from few kilowatts up to 10MW, connected to the distribution network at low OR medium voltage. Various definitions of DG are in existence and may create confusion.[Thomas Ackermann et al., (2001)] Therefore, the following definition is used.

Distributed generation is considered as an electrical source connected to the power system, in a point very close to/or at the consumer´s site, which is small enough compared with the centralized power plants.

Being the power generation near the load center, it appears to have assumed the role of an outstanding solution for many problems of energy crisis. The demand for the local generation of electricity has also arisen due to the presence of critical high technology loads which require much greater reliability than can be provided by the present system. This has created a demand for the local generation and the need for storage of energy. These factors have in turn favored DG. Starting from the period during which the concept of DG became a reality, a vast majority of scientists around the globe, have been trying to find ways to make DG more effective [H.Lee Willis, 2000, Meyer, 2000, Lorrin Philipson, 2000, Garry Rackliffe, 2000, Dugan. R.C, 2000;Welch. G, 2000]. DG is expected to change the present day, the traditional system of vertically integrated utility structure, consisting of the three major components viz. generation, transmission and distribution of electricity, which is characterized by unidirectional power flow, shown in Fig.1.1, to a modern structure comprising of the same components, permitting bidirectional flow of power, shown in Fig. 1.2. This has been appreciated by many countries which have encouraged the introduction of DG into the respective distribution systems by reforming various electric utility acts more liberally than ever. In addition, DG is also expected to offer many advantages which are discussed later.

1.2 DG Technologies

Needless to say, the fuel used must be locally available and must be economically viable. Based on the fuel used for the generation of electrical energy, a number of DG technologies are proposed in [Kroposki. B, 2000; Ramkumar. R, Chiradeja. P, 2002; Brey, J.J.Greencel S.A.,Sevilla,Spain,Castro.A,Moreno E,Garcia C, 2002; Rahman. S, 2001; Lasseter B2001; Williams. M.C., 2001], which are listed as:

- Reciprocating engines
- Micro turbines
- Small Combustion gas turbines
- Fuel cells
- Photovoltaic systems
- Small scale hydro electric power
- Wind turbines etc.

Few of these technologies are later discussed in 1.7. Each of these technologies has its own characteristics and issues. Although Tidal Power, Ocean Thermal Electric Conversion and Wave energy also are some other renewable energy sources, they are yet to be proven to be economically and technically suitable and hence are not listed here.

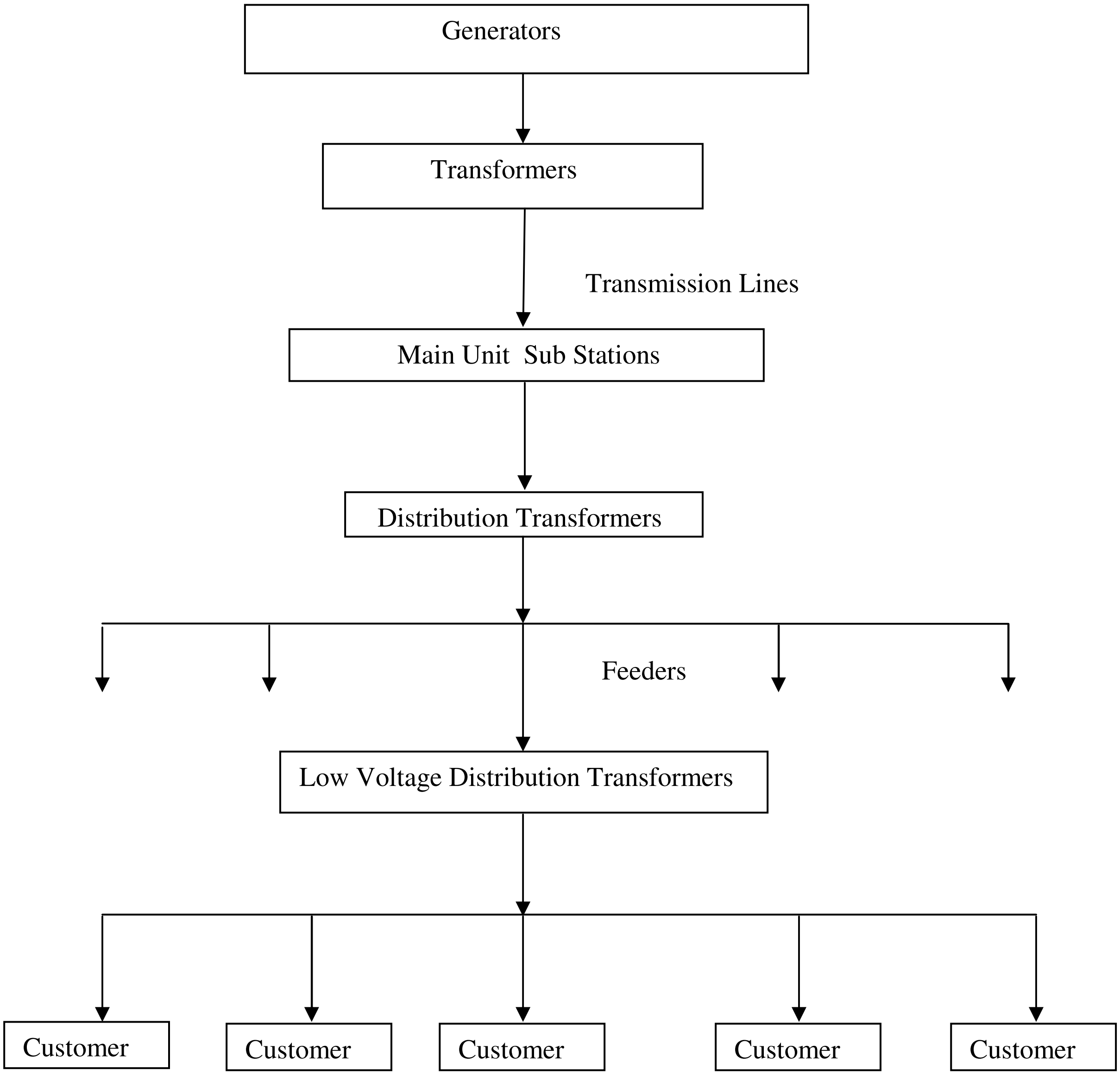


Fig. 1.1. Single Line diagram showing the Conventional Radial System

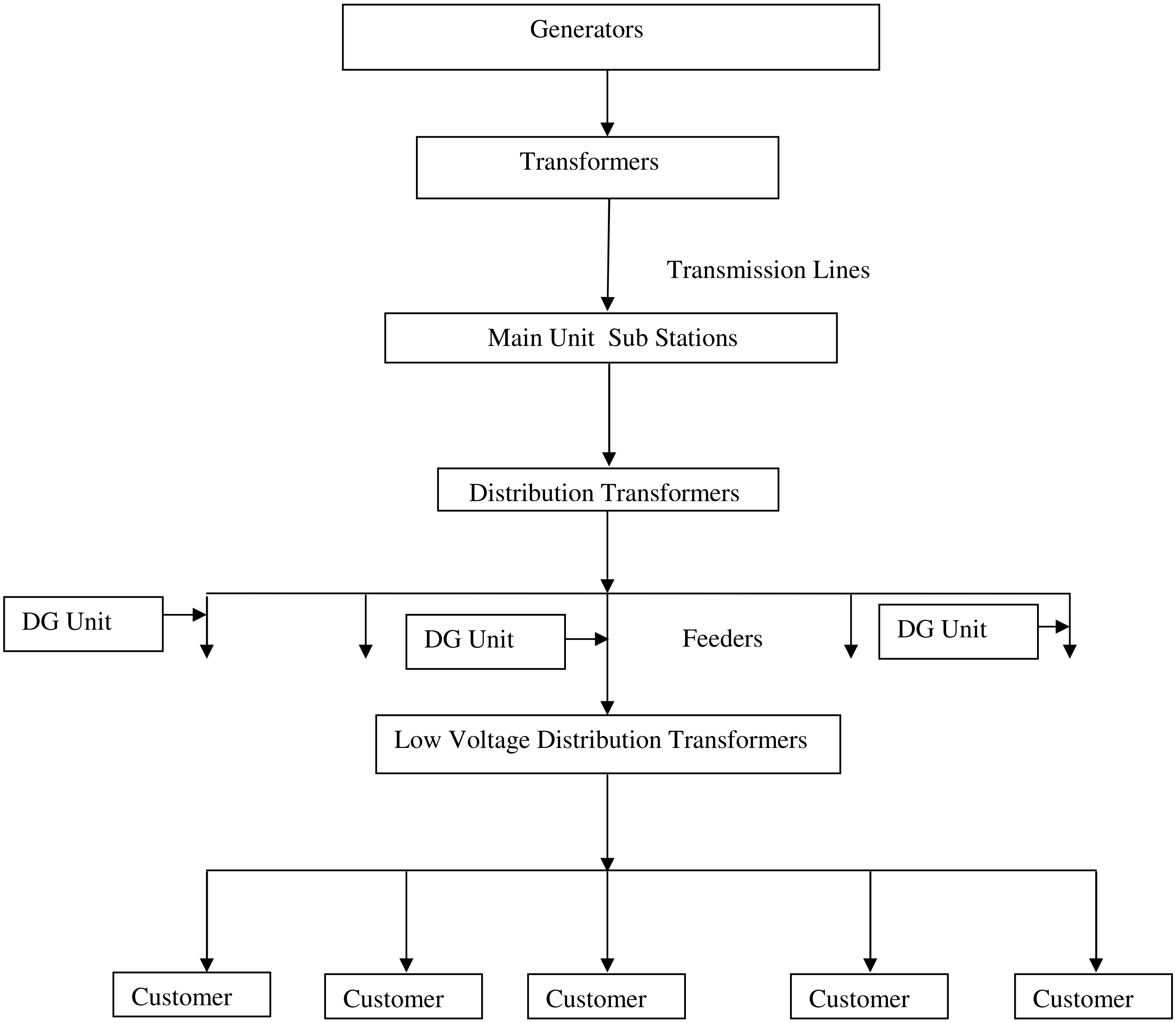


Fig.1. 2. Single Line diagram showing the Modified Radial System with Distributed Generation

1.3 Scope of DG.

Clearly there have been voices both for and against distributed generation.[16]. Those who favor DG, point out that distributed resources can improve the efficiency of the distribution system. The main argument is that there is an overall waste of energy to the tune of 4.2 to 8.9 percent due to old transmission and distribution equipment, improper implementation of reliability guidelines and heavy traffic, etc. At the same time, the power quality in the consumer's premises may not be of high quality due to many reasons such as low/high voltage, frequent interruptions, switching transients, network disturbances from the loads, etc. These arguments thus highlight the inefficiency of the existing large-scale electrical transmission and distribution network, and point out the advantages of DG related to these issues. Yet another argument is that since the customer's electricity bills include the cost of the vast transmission grid, the use of the power generation near the loads will reduce these expenses, thereby providing consumers, the quality power at a more economical rate. At the same time, those customers who can generate electricity using their own resources can sell the same to the utility and earn some income during off peak hours.[Lewes Dale, 2002]

There have been voices against the introduction of distributed generation also [Roger Dugan et al. (2002)]. These arguments say that the DG introduced in the distribution system may lower the electricity quality because of the harmonics that are introduced. It is termed as 'dirty power', which is being fed in to the system. According to these arguments, the DG may adversely affect the distribution system because of the Islanding operation of DG etc.

The past decade has seen a number of such arguments both for and against the introduction of DG into the distribution system.[Honghai Kuang, 2011]. It becomes essential, therefore to critically analyze both the sides and arrive at suitable conclusions before making any decision. Various studies conducted around the globe have examined the views of both the sides, and have opined that though DG has limitations with respect to its technology, application features, etc, it has been the best solution for the energy problems that are faced by a vast majority of the world's population. [Khan. U.N, 2008] Many industries have also begun to realize the advantages of generating power on site. Using Cogeneration technologies, thermal energy that would normally be wasted can be reused which can be supplied to the grid[www.cogen.com/br] DG has therefore become quite popular in industries like steel, chemical processing and food processing, etc..

At the same time, the disadvantages of DG also cannot be ignored. High penetration of DG into the distribution systems, results into a good number of technical issues like, protection, harmonics injected into the systems [Loo Chin Koon, Abdu Aziz, 2007], islanding operation amongst many others. Many DG resources are yet to be proved to be economic. These issues have become the major research topics and efforts are on to make DG more attractive taking the above issues into consideration.

1.4 Impacts of Distributed Generation.

As discussed earlier, it is essential to study the impacts of DG on various issues. The impact depends on several factors like the type of DG, capacity and number of DG units, the location of DG etc. Some of the impacts [Barker,P.P., et al., (2000)]can be listed as follows.

- The power distribution systems are developed for a one – way power flow and systems have been designed to take care of any situation arising in this structure. The introduction of DG will alter the structure, thus making the system more complex.
- The location of DG may affect the protection issues. Since there is a chance of reverse current flowing in the lines, the protection system must be able to act properly.
- The line losses are reduced since few sections need not have to carry the large amount of current they were carrying in the absence of DG.
- There will be an improvement in the voltage profile.
- Improvement in the reliability since DG acts as a backup power generation for some of the loads.
- Reduced environmental problems because DG employs renewable energy sources which are environment friendly.
- Deferral of investment in up-gradation of transmission and distribution lines.

1.5 Benefits of DG

Introduction of DG into the distribution network has many potential benefits which can be discussed from three different perspectives [Roger Dugan, 2002].

1. End User Perspective: This sector is greatly benefitted by DG. The end users will enjoy quality electricity with improved reliability. The DG owners can supply power to the grid, and earn revenue from the utility. If the tariff structure is such that it is lower during the off peak hours and higher during the peak hours, the owners are benefitted by supplying power to the grid during peak hours and receive power during off peak hours.[H.Lee Willis, Walter Scott, 2000]
2. Distribution Utility Perspective: The distribution system utilities will be mainly interested in supplying the energy to consumers through the existing infrastructure more efficiently and with greater reliability. DG brings about many benefits in this sector.[Mendez. V.H et al. (2006); Vu Van Thong, 2008] Some of the benefits are-
    - Increased power quality and greater reliability
    - Reduced line losses
    - Relief in transmission line congestion
    - Deferral of investments in connection with capacity enhancement
    - Peak Shaving, etc.

   Since DG facilitates the grid connection of a large number of small generation units near load centers, the power carried by the transmission lines will be reduced and therefore, DG provides a means for deferral of investment in transmission upgrades and expansions, especially at a time when such investments are quite high.
3. Society Perspective: The society is also benefitted at large by the presence of DG, in the following aspects-

- Increased availability of energy for taking up developmental activities.
- Improved environmental conditions.
- Improved economy, etc.

From the environment point of view also, DG technologies provide greater relief to society. Large, centralized power plants emit significant amounts of poisonous gases like carbon monoxide, sulfur oxides, particulate matter, hydrocarbons, and nitrogen oxides, etc. Recent studies have shown that widespread use of DG technologies reduces emissions to a considerable extent.[N.D.Strachan, www.cmu.edu/ceic.] A significant advantage of DG is that it can be a stand by for many public utilities such as medical centers, airports, defense bases, police stations, water supply stations, sewage treatment plants, radio and television and other communication services etc.

1.6 Disadvantages of DG

The disadvantages of DG can be listed as

- High cost of energy generation equipment.
- Creation and injection of harmonics into the power distribution system.
- Need for modification of the protection system, etc.

1.7 Distributed Generation in India.

Indian economy, presently growing at the rate of around 4.5 %, is expected to grow with a higher rate in the future. According to a certain survey, the Indian economy is predicted to become the third largest economy by 2030.[Jyoti Parikh, Probal P Ghosh,] With such a large growth, its energy requirement is also expected to grow considerably. Energy is considered as one of the most vital factor in deciding the country's economy status. At present, India has a total installed capacity of 205 GW[website www.powermin.nic.in] and the rate of growth is 4.5 %. Assuming that the economy grows at an optimistic rate of 8 %, within the next two decades, the installed capacity should shoot up to 950 GW [Integrated Energy policy document from website-www.planningcommission.nic.in]. In 2010, India suffered a 12 % gap in the supply and the average demand over the year and nearly 15% on peak load demand. The grid penetration of India is also not satisfactory since it is only 65% which is quite less compared to other developed countries. The situation of low-grid connectivity gets still worsened considering the fact that 70 % of the population lives in rural India. Even the grid connected rural areas suffer from the irregular electricity supply. With heavy dependency of rural economy on agriculture, this has become a detrimental cause for rural development.

With respect to the distributed generation, the situation in India is quite different than that of the western countries. Major DG technologies developed in those countries have a very little relevance in Indian context because of the following:

- The high cost of energy produced using IC engines and gas turbines.
- Very few suitable sites available for wind energy.
- Fuel Cell technology, till date, is extremely expensive.
- Growing concern about environment and stringent emission norms make generation from fossil fuels makes it economically unviable.
- Irrelevance of CHP plants.

1.8 Renewable Resources for DG in India:

The main technologies that use renewable sources for the distributed generation in India are:-

a) Mini/Micro Hydroelectric Power : India's hydroelectric potential has been assessed at 1,48,700 MW out of which only 36878 MW (24.8%) is installed [Indian Renewable Energy Status Report 2010 from website-nrel.gov/docs]. The estimated utilizable surface water resource is 690 cubic km providing a rich source of hydroelectric development. There are 6 major river basins draining the country all of which when taken together amount to about 25, 28,084 sq km of catchment area. Most of these river basins have already been tapped for the power generation and further projects in areas excluding north eastern region, may lead to environmental problems.

At the same time, some of the projects were turned down either because there was a possibility of deforestation or due to requirement of evacuation of large population.

However, there are a large number of small/medium river basins comprising west flowing rivers in the states of Gujarat, Maharashtra, Karnataka& Kerala and east flowing rivers in Orissa, Andhra Pradesh, Tamil Nadu and Bihar. These rivers are best suited for small and mini/micro hydroelectric power plants. Besides, the establishment of these small or mini/micro hydroelectric power plants is quite simple because these plants do not need large reservoirs. Hence, these small, mini, and micro power plants are best suited for the distributed generation in India.

India has a potential of 15000 MW from Small Hydel Plants (SHP). At present, 674 small hydropower projects up to 25 MW station capacity with an aggregate capacity of over 2429.77 MW are installed. Over 188 projects in this range with aggregate capacity of 483.3 MW are under construction. 13 States in India, namely, Himachal Pradesh, Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Karnataka, Kerala, Andhra Pradesh, Tamil Nadu, Orissa, West Bengal, Maharashtra and Rajasthan have announced policies and have invited private sector for setting up commercial SHP projects.

b) Solar PV Generation :

India is blessed with vast solar energy potential. About 5,000 trillion kWh per year energy is incident over India's land area with most parts receiving 4-7 kWh per sq. m per day [Indian Renewable Energy Status Report 2010, www.nrel.gov/docs]. Hence, there is abundant scope for effective utilization of solar energy for both the processes viz. solar thermal and solar photovoltaics. Solar can also be considered as an effective resource for the distributed generation. Especially for rural areas, this turns out to be a most useful technology for both on and off-grid applications. At present the installed capacity is only 424.9 MW which clearly shows that this potential is not tapped properly. The chief constraint for solar energy conversion system is that it requires large space. However, various state Governments have started planning to harness the solar energy effectively. With the cost of equipment reducing, PV systems have a great potential to compete with conventional sources.

Currently, more attention is being paid to large-scale solar PV projects. In Phase 1 of Jawaharlal Nehru National Solar Mission (JNNSM), India aims to install 500 MW of grid-connected solar PV power. New PV projects are also being registered under state government programs in many states, such as Punjab, Gujarat, West Bengal, Rajasthan, and Karnataka, though many of these are being migrated to JNNSM. The mission allows, the creation of special economic zones, which provide land, water, and power as well as financial incentives to the domestic industries, due to which the domestic manufacturing has increased considerably.

c) Wind Energy

India’s wind energy potential is 1,02,788 MW assessed at 80 m Hub height. The present installed capacity is only 16078 MW amounting to only 15.64 % of the potential [Indian Renewable Energy Status Report 2010, www.nrel.gov/docs]. This shows that wind energy can answer the power shortage problem considerably if it is properly harnessed. However, the major barrier for the wind energy plants is the high initial cost of the wind turbines and the availability of space at the specified sites.

The C-WET resource assessment program has estimated the potential for wind installation for nine states. The assessment shows that India's total wind potential is 48,561 MW, with Karnataka, Gujarat, and Andhra Pradesh as the leading states. However, the Indian Wind Turbine Manufacturers Association argues that by looking at higher heights above the ground to match 55–75 m turbine hub heights of the latest turbines and taking into account higher conversion efficiencies due to recent improvements in wind technology, the wind potential in India is closer to between 65,000 and 70,000 MW.

In March 2006, India had approximately 5,300 MW of installed wind capacity. Between 2006 and 2009, the annual rate of wind capacity additions decreased. In certain states, however, as new markets opened up, growth rates were above average. For example, between 2008 and 2009, annual growth rates of installations were 37% in Rajasthan, 33% in Karnataka, and 25% in Gujarat, while the average across India was 17%.

In terms of electricity supply, in 2007, wind projects supplied 11,653 GWh to Indian consumers, representing a 1.45% share of the total electricity produced in India that year.

d) Historically, traditional biomass has been a major source of household energy in India [Indian Renewable Energy Status Report 2010, www.nrel.gov/docs]. The majority of the rural population in India use wood and cow dung as the main source of energy for daily requirement even today. This amounts to nearly 40 % of the total energy supply. Various processes facilitate easy conversion of the available bio mass in to more useful energy forms like the electrical power and heat/steam, etc. Biomass resources in India are used for power generation through three general applications: grid-connected biomass power plants, off-grid distributed biomass power applications, and cogeneration via sugar mill and other industries. The amount of biomass resources in India is estimated about 565 million tonnes per year, including agricultural residues and forest residues. The surplus biomass resources which is not used for animal feed, cooking, or other purposes, and is available for power generation annually, is about 189 million tonnes, which could support roughly 25 GW of installed capacity.

MNRE reported that 10 biogas projects using industrial waste, with a total capacity of approximately 10 MW, were completed during 2008–2009. These included 1.40 MW of installed capacity at a distillery in Tiruchirapally (Tamil Nadu), 3.66 MW using poultry litter in Dupalapudi (East Godavari District, Andhra Pradesh), 0.69 kW at a distillery in Ahmedhnagar (Maharashtra), 1.00 MW using starch waste in Gujarat, and six projects in the states of Maharashtra, Uttarakhand, Madhya Pradesh, Karnataka, and Tamil Nadu with a total capacity of 3.19 MW using liquid waste from the food industry and tanneries. Additionally, eight projects with an aggregate capacity of approximately 14 MW were completed in 2009. These included five projects totaling approximately 12 MW installed capacity at distilleries, two 1 MW projects using waste from starch factories, and one small project generating biogas from yeast waste. Under BGPG, 65 new projects with a total installed capacity of 0.353 MW were initiated in the states of Andhra Pradesh, Chhattisgarh, Kerala, Maharashtra, and Uttarakhand during 2008–2009. Approximately 14 additional projects were initiated during this time in Tamil Nadu and another 11 projects in Kerala. During 2009–2010, one new project was initiated in Haryana and several project

proposals were received from the states of Andhra Pradesh, Goa, Maharashtra, Tamil Nadu, and by Khadi and Village Industries Commission. The total installed grid-connected biomass power and bagasse cogeneration capacity was 2,322 MW at the end of June 2010.

e) Internal Combustion Engines: Perhaps these types of DG units are widely found in almost all industrial plants. However, due to the high cost of diesel, the cost of generation using diesel is very high i.e. Rs.10-12/- per kWh considering life / upkeep of engines. Thus, IC engines are not economically viable for the main power generation and hence these are used as standby sets invariably. In extreme emergencies, in the remote places where the grid has yet not reached, these units are used as Base Power Generators. Extensive usage of these sets can also be found at construction sites where it takes 3-5 years to complete and would not like or do not have Captive Power from utility till the plant becomes functional. It is estimated that the Industrial Power-generating capacity amounts to 15 GW out of which 6 GW is by diesel generation.

f) During recent years, the idea of using the Municipal Solid Waste for power generation is gaining considerable importance. With the fast growing population and the resulting growth in the waste generated, this has been identified as a very good resource.

In the present work, Solar PV generation and Power Generation using Municipal Solid Waste are considered as the resources for distributed generation and the possible grid connection to a selected Feeder in the city of Dharwad. Both the resources are analyzed for useful power production later.

1.9 Problem Statement:-

1. To find the suitability of the following distributed generation resources and modeling them.
    a. Solar PV and
    b. Municipal Solid Waste.
2. To quantify the following benefits of DG:-
    a. Loss Reduction in the distribution system.
    b. Voltage Profile Improvement.
3. To study the impact of DG on the following:-
    a. Estimation of Fault Location.
    b. KVA delivered by the source.
    c. LV side faults.

The research thus has dual purposes. On one hand, it focuses on the need of effective utilization of the resource available and on the other hand, it analyses the impacts of DG with respect to the line loss reduction, voltage profile improvement and the estimation of the fault location and proposes quantification indices for some benefits.

Appropriate mathematical models of each of these technologies have been discussed later in chapter 3. The approximate cost of energy generated using these two technologies is estimated.

1.10 Method of Study

The evaluation and quantification of some of the benefits of DG have been proposed in this investigation, using mathematical models which are used in this research. The steps followed to achieve the objectives are

1. Mathematical model for the solar pv generation is developed. Since the solar insolation is random in nature, probabilistic model using beta distribution for the cloud cover is used in the research.
2. Suitable model for the power generation with the Municipal Solid Waste as fuel is developed. The samples of waste were collected, tested in the laboratory to assess the suitability as a fuel and the entire process was modeled mathematically using linear equations. The economic viability of the project is also carried out using cost function as an optimizing function.

3. A feeder in the city of Dharwad was chosen for the study and was simulated.
4. Both the sources mentioned above were connected to the feeder and the simulation results were obtained with and without distributed generation and were analyzed.
5. A new quantification index for the Line Loss Reduction is realized and proposed after comparing with the earlier index.
6. A new method of quantification of the voltage improvement benefit is evaluated and proposed.
7. A number of case studies are selected and the analyses are carried out in support of the quantifications suggested and the results are obtained.
8. The impact of DG, on protection issue was analyzed by obtaining the fault location estimations with and without DG.
9. Some useful conclusions are drawn from the research and the future work is suggested.

1.11 Outline of the thesis:

The thesis is divided into 7 chapters including the introduction. A brief content of various chapters are given here:-

Chapter 2 Literature Survey

In this chapter, an effort is made to consolidate the achievements of various authors, related to DG technologies and the impacts of DG. Since the day the concept of DG was brought into reality, many researchers and scientists worldwide have contributed to the growth of distributed generation. The report presented here is not exhaustive. While every effort is made to cover the all the aspects of the field, certainly one may find a lot more information about the topic in the literature. Only those reports which are pertaining to the field of study are taken and discussed here.

Chapter 3 Proposed DG Technologies.

This chapter presents discussion and modeling of two DG resources: solar PV generation and the power generation using municipal solid waste. The solar insolation is one of the very few, most freely available, renewable resources in the world. In this investigation, a probabilistic method employing the cloud cover as a random variable is used to develop the model for PV generation. The roof top space of a school is identified and using the model developed earlier, a suitable solar panel is selected yielding a power output of 270 kW (peak).

The second source of energy considered in the investigation is the Municipal Solid Waste abbreviated as MSW. This chapter also describes the method which is used to develop a model for the generation using MSW as a fuel. The power generated is arrived by knowing the calorific value and the incinerable weight, which is found to be 19930 kWh per day. Hence an alternator of 800 kW is selected for the generation.

Chapter 4.0 Quantification of Benefits of DG.

This chapter describes the proposed quantification of the benefits of distributed generation. Out of the many benefits, two benefits are quantified here. They are:

a. Loss Reduction
b. Voltage Profile Improvement

Chapter 5.0 Other Impacts of DG

This chapter deals with some of the other impacts of DG on the power distribution system. Out of many impacts the following issues have been analyzed in the present investigation.

a. Estimation of the fault location:- Faults in a distribution system are inevitable and cannot be avoided. The presence of the fault should be detected immediately and it should be cleared instantly to avoid any further damage. The fault can be detected by measuring the voltages and currents at a specific node which vary with the occurrence of the fault. [J. Faig, et al., (2010)] The location of the fault is then determined by using the impedance method which utilizes the fundamental components of the voltages and currents measured at the substation.(R. Das. 1998). The presence of the DG in the system, however has a significant effect on the substation currents and hence the estimation of fault location will be affected. In the present work, faults are simulated and the fault location estimates are obtained with and without DG. Out of many types of faults, only the single line to ground fault is considered in this investigation.

b. kVA delivered by the source: One of the major advantages of the distributed generation is that the burden on the source is reduced. However, this solely depends upon the operating power factor of the DG unit. Majority of the loads on the power distribution network are inductive in nature and demand reactive power for their operation. If the DG unit is operating at unity power factor (as in case of solar PV generation), the required reactive power has to be supplied by the source and the total kVA therefore increases. It is therefore essential to study this issue before fixing up the operating power factor of the DG source.
c. Faults on the LV side : When a fault occurs on the HV side, the substation currents change significantly and the fault can be detected by measuring these values. If a fault occurs on the LV side, it is shown here that the changes in the substation voltages and currents are very small and these may be misunderstood for the changes due to the load variations. If the protection circuit does not operate on the LV side, this situation continues and a large power continues to flow through the faulty line. The situation becomes still worse with the presence of DG in the system. This has to be properly taken care while installing the DG.

Chapter 6.0 Results

A practical distribution system consisting of 35 transformers is selected for the study. The feeder detail is collected and is simulated using CYMEDIST software. The solar powered DG unit is connected to the grid at node No 26 and the DG unit using the MSW derived fuel is connected at node no. 41. The load flow studies are conducted for varying conditions of DG and loads. SLRI and VRR are evaluated for all the conditions and are presented.

Simulation results for Loss Reduction:- The variation of SLRI shows that the losses in the system can be reduced by increasing the DG ratings. However, high penetration of DG will increase the losses than reducing them. The simulation results reveal that SLRI is greatly influenced by the power factor of the DG unit. In case, the unit is operating at unity power factor, all the reactive power required by the load is supplied by the source and hence, there may not be any appreciable decrease in line current supplied by the source, leading to higher losses and thus low SLRI. Further, it can be seen for increased penetration of DG that the index may exceed unity, indicating that the presence of DG has increased the line losses than decreasing it. This factor should be considered while fixing the operating power factor of DG. The Loss Factor remains fairly constant and hence the loss reduction depends mainly on the current injected by the DG unit. When I_G is more than the feeder current, loss factor becomes positive and the total losses in the system increase, leading to SLRI acquiring value greater than one. The location of DG is also very critical in deciding the loss reduction. SLRI show a decreasing trend when DG is located away from the substation. This issue should be considered before installing DG in the system.

Simulation results for voltage profile improvement:- The voltages at all the nodes are found to increase with DG incorporated in to the system. To illustrate this, two nodes are considered in this investigation. One node is nearer to the substation and the other is away from the substation, nearer to the remote end. It is seen from the simulation results that as the output of DG increase, VRR decrease indicating rise in the node voltages. However, higher penetration of DG may result in node voltages becoming more than the base voltage. This is because of the reverse flow of current in the feeder segments. DG operating power factor also influence VRR. As the operating power factor of DG changes from lagging to leading, VRR increases indicating that the node voltage has decreased.

Simulation results for Estimation of Fault Location: In the present investigation, a single line to ground fault was simulated at two different locations: one before the DG and one after the DG. For each of these cases, the fault location estimates are obtained. It is observed that those estimates obtained in the presence of DG, produce more errors than the estimates which were obtained without DG.

Simulation Results for kVA delivered by the substation: The most important benefit and common understanding of embedded generation is that substation delivers less power in the presence of DG than in the absence of DG. This is found to be partially true because, though the statement is true for active power, the same is not true for reactive power in the case when the DG is operating at a different power factor than that of the load. If the DG operates at unity OR leading power factor, the loads have to draw reactive power from the supply lines itself, thereby increasing the kvar burden on the lines. Hence kVA is not proportionately reduced by the presence of DG. From the investigations, it is very clear that even if a DG supplies one-third of active power of the load, the source has to deliver almost same kVA as it would have delivered in the absence of DG. This point has to be considered while fixing the operating power factor of DG. This issue is of great concern with solar PV generation since, the solar PV generation always operates at unity power factor.

Simulation results for Faults on LV side : Faults occurring on the LV side of the distribution system are hard to detect by monitoring equipment because their presence result only slight increases in substation current and hence can be confused with a normal increase in load. The condition becomes worse with the inclusion of DG into the system since the currents drawn from the source will have a very marginal increase. Several comparisons are drawn by obtaining the currents and the voltages on the substation side under such fault conditions with and without DG.

Chapter 7.0 Conclusions

This chapter specifies the conclusions drawn from the simulation and mentions the scope for future work which include

- The estimation of fault location needs further studies to include the effect of higher penetration of distributed generation.

- The issues arising out of the operating power factor of DG on the kvar supplied by the source needs to be addressed and a power factor correction arrangements at the substation side needs investigation.

- The faults on the LV side are not usually noticed at the substations since the change in the current and voltage values at the substations are usually mistaken for the change in loads and therefore the faults may not be detected at all. This is more severe with high penetration of DG. This issue needs further analysis.

CHAPTER 2

BACKGROUND

(Literature Review of the related DG Technologies and Impacts of DG)

The Power Distribution Systems are traditionally radial, the power flowing in one direction. The concept of integrating DG units has given a new dimension to this traditional system. With the embedded generation, power flow direction in some of the line segments may change making the analysis more interesting. The suitability of DG has been the main concern and there have been many voices in favor of DG.

The initial introduction of DG can be found in [P.R.Van Horne et al. (1981)]. The earliest concept of Distributed Generation was possible to come in to reality because of the USA's Public Utility Regulatory Policies Act (PURPA) in 1978.[Roger C. Dugan and Dwight T. Rizy, 1984]. Initial studies on the saving of power transmitted due to the presence of the dispersed generation can be found in [P.R.Van Horne et al. (1981)]. The monitoring and control requirements for dispersed storage and generation were studied in [Harold Chestnut, 1982]. The protection issues in systems with the dispersed generation were studied in [Roger C. Dugan and Dwight T. Rizy, 1984]. The idea of the small power generation then took great momentum and has been the focus of many researches since then. There are many issues concerned with the Distributed Generation, the first being the appropriate DG Technologies.

The use of appropriate DG Technology depends on the locally available resource and the feasibility of using the same for power generation. A number of DG technologies have been recognized. These technologies include solar PV generation, wind power generation, fuel cells, mini and micro hydroelectric power plants, etc among others. All these resources may not be useful everywhere. Looking into the resources available and the possibility of establishing small power plants, two technologies viz. Solar PV Generation and Power Generation from Municipal Solid Waste have been identified for the proposed power generation in the city of Dharwad. These technologies have been given more attention in this work.

2.1 Mathematical Modeling of the DG Technologies

To validate the suitability of any DG technology, the same has to be properly modeled. The proposed installation of distributed generation uses two sources of energy: the solar PV energy and the Municipal Solid Waste. Hence, these two energy sources are mainly considered here. The solar PV generation depends on the insolation which is highly random in nature. Hence probabilistic model is most suitable for modeling the same. The power generation using the Municipal Solid waste is very simple since it uses a normal generator which can be modeled with a linear relationship between the fuel input and the energy output. However, the processing of MSW is complex and the heat available from the MSW can be modeled using linear equations.

2.1.1 Modeling of Solar PV Generation

Modeling solar pv generation requires the accurate value of the energy available and hence involves complex steps because of the random characteristics of the insolation. Accurate prediction of insolation is not possible and therefore only the stochastic analysis can be used to give acceptable estimations. Although a large number of models are available at the component level for the solar PV generation, the models which relate the solar insolation and the power generated invariably use the probabilistic approach since the solar insolation is highly random in nature.

The insolation modeling was presented in [Young. K.L, Woo. M. and Munro. D.S, 1995], where the radiation model was developed under clear sky conditions. The radiation obtained was then modified using various cloud models. The concept of cloud layer approach was introduced. As a result, the solar radiation at any instant can be modeled by considering (a) model under clear sky conditions and (b) the cloud layer model. However, the model requires a large quantity of data and was thus suitable only in places where metrological data can be collected. Moreover, the model can be used only for the Arctic location, where the meteorological data are collected.

Similar approach was used in [Abouzahr. I. and Ramkumar. R, 1991] where, the cloud cover was taken as a random variable and the authors found that beta distribution is most suitable for this random variable. The insolation during a bright sunny day was considered as maximum and the insolation at any other time was expressed in terms of the maximum insolation. The cloud cover is defined as something which covers the sun. During the instant of maximum insolation, the cloud cover is zero and during nights when there is no sunlight, the cloud cover is one. Thus the cloud cover varies between 0 and 1.

A work related to the moving cloud is introduced in [Jewel. W. and Ramkumar. R,1987]. The authors investigated the effect clouds on the photovoltaic generation. They developed a cloud pattern which was described in terms of size, shape of individual cloud, the percentage of sky covered by the clouds, the speed and direction of the cloud movement etc. However, the estimation of such requirements need more accurate prediction and reorganization of cloud pattern.

In this work, the method suggested in [Abouzahr. I. and Ramkumar. R., 1993] is employed and the modeling of power output in Dharwad, during daytime only is obtained.

2.1.2 Modeling of Power Generation using Municipal Solid Waste.

The disposal of Municipal Solid waste vis-à-vis the power generation using the waste, has been a field of interest for more than 5 decades. The suitability of MSW for the electrical power generation has been established by many researches. The work carried out in [A. Porteous, 1993], analyses the development and the environmental impact of power generation from MSW and Landfill operation. The authors favor the incineration as a safe method of waste disposal in addition to the power generation. The suitability of MSW for incineration and Landfill facilities was studied in detail in [Ketlogswe, 1996], which studies the co-combustion of MSW and the industrial waste from the point of power generation. They showed that the incineration of a mixture of coal and MSW would produce clean environmental results in addition to energy.

A detailed analysis on the MSW fuelled Power Generation for India was carried out in [C. Palanichamy, 2002]. The authors made a detailed survey based on several criteria and studied the suitability of the scheme for Madhurai City. The incineration of MSW to produce electricity in India was later studied in detail in [P. Chandrasekar, S et al. (2005)]. The authors analyzed the MSW to assess the waste heat potential and pollution problems. They concluded that the incineration serves economical on the extraction of power and an effective waste reduction for regaining the investment in a shorter span of years. The proposal revealed that though the incineration process would incur a high capital cost compared to wind power project, the cost can be reduced if proper environment friendly technologies are practiced and also by using the indigenous machineries and equipments.

The mathematical modeling of solid waste management was presented in [Eric Solano, et al. (2002)] which describe various waste flow processes. Every waste has to pass through a number of waste flow processes before reaching the final process. For every waste flow process, there are many waste flow paths. Linear equations can be developed for every waste flow paths and for every waste component. The total waste that is processes can be expressed in terms of these linear equations. This equation can be optimized for any function such as cost function, environmental impact etc. The model for cost function, environmental impact function were developed using linear equations.

The characteristics of the energy flow in the incinerator are studied in [Moo Been Chang and Chien Kun Huang, 2001]. The heat loss of the incinerator, heat absorbed by the boiler, heat loss in air pollution control devices and the heat discharge from stacks were considered and thus the total incinerator capacity was arrived at. A spreadsheet model for material balance was developed in [Douglas A. Haith, 1998], as an accounting procedure for determining the impacts of management decisions on the physical scale and the productive outputs of the MSW management system. The model takes care of all possible processes: source reduction, recovery, composting, waste to energy, and landfilling. The landfilling of MSW on a life cycle perspective was separately studied in [Wanida. W, 2003]

In the present research, a mathematical model for the power generation for Dharwad is taken up using the cost function as a variable.

2.2 Impacts of Distributed Generation on the Power Distribution Network.

The penetration of DG into a power distribution network has many impacts. These impacts may be the benefits caused by the DG or they may be the negative issues created by DG.

2.2.1 Line Loss Reduction and Voltage Profile Improvement.

Perhaps this has been the major focus since the introduction of DG. When a DG is installed in a Power Distribution System, there will be a number of benefits for all the stakeholders. The benefits of DG are based on rating and location of the unit. Many benefit analyses have been carried out and have been quantified. This section covers a brief literature review the previous work carried on the quantification of benefits.

Before a distributed generation is practically implemented in a distribution network, it is customary to find out why the DG is necessary from both the customer's point of view as well as from the viewpoint of the distribution utility. In addition, it is also necessary to learn the economic benefits of the proposed system. The earlier literature survey showed that the DG is favorable to the power system as a whole and the society in general. However, the extent of such benefits has to be clearly understood.

The potential benefits of DG on power delivery systems were studied in [Peter Daly and Jay Morrison, 2001]. The authors gave an example method to analyze the potential benefits of DG and gave an elaborate methodology for assessing benefits of DG. The authors showed that the power delivery savings are significant but they should match with additional customer benefits to make DG more economical.

The transmission loss allocation was studied in [A.J.Conejo, et al. (2002)]. In the liberalized electricity market, the generators record, the actual energy generated and the bidder will get paid for that while the meters at the consumer's premises record, the actual energy consumed and consumers will pay for the actual energy consumption. This procedure does not specify about the losses and the question of who should pay for losses will arise. The authors have analyzed three families of analysis : prorata procedure, marginal procedures and proportional sharing procedures.

A similar study is made in [Paulo Moises Costa and Manuel A Matos, 2004]. The authors here gave a very simple solution. The losses in the distribution system in the absence of DG are allocated to the consumers while variations in losses that result from the influence of DG are allocated to the generators. In the proposal, both active and reactive power losses are considered.

The benefits of DG were quantified in [P. Chiradeja and R. Ramkumar, 2004]. The authors considered various impacts of DG and proposed methods for quantification of the benefits. They proposed several indices : LLRI for the line loss reduction, VPII for the voltage profile improvement, EIRI for the Environment impact reduction and an overall benefit index BI. A standard 12 bus system was considered and the benefit indices were derived. The voltage profile improvement index was quantified as a ratio of the voltage profile with and without DG. Each bus was assigned a weighting factor thereby differentiating between the critical and normal loads. If VPII >1, the inclusion of DG has benefitted the system. The Line Loss Reduction Index (LLRI) defined as the ratio of the line loss with DG and the line loss without DG for the same amount of load on the system. If LLRI <1, the insertion of DG has benefitted the system. Similarly, other index, EIRI defined as the ratio of the amount of emissions with DG to that without DG for a particular pollutant and the overall EIRI takes the reduction indices of all such pollutants. Finally, a comprehensive index Benefit Index (BI) was proposed, which gives the overall benefit of DG considering all such benefits. It was also shown that these indices were dependent on the rating, location and the power factor of the DG. It was shown that losses can be reduced by nearly 46% for a particular location, rating and a particular power factor. However, the indices were obtained for a test system with 12 buses and only the feeder lines were considered. The LLRI is highly optimistic since the Low Voltage losses are not considered which amounts to a greater portion and which remains constant in a practical distribution system.

The Line Loss reduction benefit of DG was analyzed and quantified by [P. Chiradeja, 2005]. The per unit loss reduction (PULR) was obtained as the ratio of the loss reduction with DG to the line loss without DG. The PULR was calculated for varying DG ratings, operating power factors and ratings. The work also revealed that the line loss reduction becomes negative if the penetration exceeds twice the system loading.

The voltage profile improvement index was refined by [H. Iyer, S. Ray and R. Ramkumar, 2005]. The authors proposed two indices : $VPII_1$ and $VPII_2$. These indices are modifications of the earlier VPII and take a simple quadratic form so that they can be taken as an objective function to find the optimal location of DG.

There have been a good number of researches on the optimal positioning of DG for power loss minimization. [M.A.Kashem, 2006], proposed techniques to minimize power losses in a distribution system by optimizing the DG model in its size, location and operating point. The method employed both the constant current and constant current modeling for the loads. Both the active and reactive power losses were considered. The present practice for loss estimation in distribution feeders in India is discussed in [P.S. Nagendra Rao and Ravishankar Deekshit, 2006]. The authors highlighted the difficulties in measuring LV losses and proposed a method to measure the same. The method depends on knowing the load ratings connected on any segment and also on the entire feeder. The optimal placement of a DG in a distribution system is proposed in [T. Gozel,, 2005]. The authors considered all the types of loads: Uniformly Distributed Load, Centrally Distributed Load and Increasingly Distributed loads and suggested optimal placement and sizing of DG. The economic benefits of the DG were modeled and quantified in [Hugo A. Gill and Geza Joos, 2008; Ajay-D-VimalRaj et al. (2008)]. The authors developed models that allow the quantification of the benefits of DG in economic terms. The models developed regulates the economic conditions so that utilities are constrained not to charge the connection fees to the owners of DG units since they actually reduce the losses and help in providing reliable supply. The effect of increased penetration of the DG units on the energy distribution losses was studied in [Victor H, et al. (2006)]. The work points out that though the DG reduce losses, it is always not true. The authors propose an approach to compute annual energy loss variations when different penetration and concentration levels of DG are connected to the distribution network. The paper also studies the impact of losses on different DG technologies. They showed that the energy loss variation, as a function of the DG penetration level takes a characteristic U shape trajectory. [Luis F. Ochoa, 2006] Carried out the evaluation of DG impacts with a Multiobjective Index. Various issues like line losses, voltage, the current capacity of conductors and short circuits are considered and a single index comprising of all the indices pertaining to the above issues was presented.

2.2.2 Stability and Reliability of the power distribution system with DG.

Ahmed Azmy and Erlich. I[2005], studied the impact of significant DG penetration on the stability of distribution network and found that DG can improve the stability of power systems if suitable types and appropriate locations are selected. The authors conducted study on a large network with two power plants and many DG units. The impact of DG on the transient stability of the power system was studied by Slootweg J.G and Kling W.L[2002]. The technologies of the DG units are usually different than those for bulk power generation such as the squirrel cage induction generator, high or low speed generators and PV modules that are connected to the grid through a power electronic converter. The effect of these units on the power distribution network will be negligible will be negligible when connected in small numbers. However, when the penetration level becomes higher, the DG starts influencing the dynamic behavior as a whole. Two stability indicators were used in the work both without DG and with DG at various penetration levels. A scheme for stability control for DG systems was proposed by Zhengui L., Zeng X., Shuntao T. and Zigang G.(2004). They proposed a control method for the emergency state. The reliability Impact of DG was studied by Many researchers. [Richard E. Brown. et.al., 2001; A.A. Chowdhury, et.al, 2003; In-Su Bae and jin-O-Kim, 2003]. It was shown that DG improves the reliability of the feeder since, it is able to supply part of its own load and transfer partially the power to those interconnected feeders which don’t have DG connected. A technique, using the load duration curve to evaluate reliability was introduced and reliability indices were evaluated. They showed that with the proper generator rating for DG, determined using the reliability technique, the inclusion of DG, may become the cost- effective solution for all the energy problems in the future.

2.2.3 Faults and Protection

The inclusion of DG is found to disrupt the protection system of an existing power distribution system. The presence of DG makes current to flow in the reverse direction in some sections and in the event of fault, part of the fault current is supplied by these units, thereby necessitating change in protection system settings.

[Michael T. Doyle, 2002], analyzed the Impact of DG on system protection and coordination when DG is added in the system with existing line reclosers and fuses. [Thomas G, Martinez L and Danijela K], conducted a study on the protection issues of a 38 KV distribution network with the inclusion of DG. The advent of widespread DG provides an opportunity to a number of IPPs to supply power to the grid. This creates multidirectional power flow situations on few parts of the system which were originally designed for unidirectional flow only. This situation restricts the operation of the protection system causing false tripping. Several case studies were studied and the impact of DG was established. The impact of DG on the overcurrent protection of a radial feeder was studied by [James, et al. (2007)]. These authors conducted a study on IEEE 34 node test feeder and found that DG does not adversely affect protection selectivity and coordination for penetration levels of 20 % of the original feeder load but the overcurrent protection has to properly modified so that the circuit remains correctly protected for specific DG cases. [Thekla N.B.et al. (2008)], calculated the fault level in medium and low voltage distribution network with DG using the IEC 609609 standard. The authors stressed the need for revision of IEC and IEEE standards to include the effect of DG resources.

The major step in fault clearance is the detection of the fault and the estimation of the fault location. These two tasks are usually carried out using the measured values of voltages and currents at one point. With the inclusion of DG, these values may alter and may not give accurate estimations.

[Faig, J. Melendez, et al. (2010)], carried out a study on the fault location algorithm with various positions and ratings of DG and discussed the effect of DG on the estimation. [Arturo Suman B. and Rodrigo Hartstein S.], proposed a new fault location technique for distribution feeders with the distributed generation. The authors used the positive sequence apparent impedance for the estimation. DG units are modeled as synchronous generators. Similar studies were conducted in [Jose Ubirajara N.N. and Arturo Suman B, 2011]. The impact of different types of faults at various locations on a distribution system with and without DG was studied by A.S.Safty [A.S.El.Safty,et al. (2010)].

At the present time there is very little literature available on the impact of the distributed generation on a practical distribution in India using locally available energy resources. Practical systems differ from the hypothetical systems to a significant extent. At the same time, the loss indices defined earlier include only feeder line losses and the system losses have not been considered. A methodical approach is the need of the hour to correctly quantify and assess the benefits of DG for a practical system and arrive at the best location and ratings of the DG to avail maximum benefits.

CHAPTER 3

DG TECHNOLOGIES

As discussed in chapter I, the DG technologies suitable for India are mainly Solar PV generation, Small and Mini hydro power plants and Wind energy. This chapter focuses on identifying suitable resource/s for DG in Dharwad and modeling the same.

The most promising renewable resource for power generation in Dharwad is Solar Energy. Small/mini hydro power plants cannot be established because the city is deprived of rivers. Wind power plants are also not feasible because of the inadequate wind speed. From the sustainability point of view also Solar Energy is the right candidate for power generation. Therefore, in this investigation, solar energy is selected as one of the resource for power generation in Dharwad. In addition, it is noticed that the city has another potential resource for energy generation in the form of Municipal Solid Waste. The total waste collected in the city is nearly 1.4 tonnes and taking the clue that power can be generated from waste, the same is selected as another resource of energy in Dharwad.

In this chapter, solar PV generation and electrical power generated using MSW as fuel have been studied and modeled. A preliminary analysis of the economic aspects is also carried out and is outlined at the end of the section.

3.1 PV Generation

Photovoltaic devices convert the solar energy in to electrical energy. The nuclear reaction in the sun yields a huge amount of energy (about 389 x 10^{24} W). Of this, only a small fraction is intercepted by the earth’s surface, with an average value of 1370 W/m^2 at the outer atmosphere [Paul Burgess, 2009]. If this energy is tapped properly, the energy will be sufficient to meet the total demand of the globe and even there will be a huge excess energy left unutilized also.

The solar PV generation has the advantages that it is clean, low maintenance and absence of recurring costs, etc. The range of PV cells varies from few watts to several megawatts. It is suitable both for a large central power station of several hundreds of kW as well as a small DG unit of few kilowatts.

A PV cell consists of two layers of pure crystalline silicon [Sukhatme, 1996]. The layers have a surplus of electrons on one side and a deficit of electrons on the other side, because of the doping with boron on one side and phosphorous on the other side.

When the surface of the cell is exposed to sunlight, the excess electrons, from the layer with high concentration of electrons, are released. A potential difference (which is around 0.5 volt in Silicon) is thus created as these excess electrons try to move to the other side where there is a deficit of electrons. Metallic contacts are made on both sides of the semiconductor. When an external circuit is connected to the metallic contacts, which are placed on both sides of the semiconductor, the electrons start flowing, giving rise to a current flow through the circuit. However, the PV cell cannot store the energy; instead it acts as an electron pump.

The solar cell can be regarded as a combination of a constant current source, a diode and a load connected at the terminals.[E Lorenzo, 1994] The simplified equivalent circuit of the cell is shown in fig 3.1. This simplified model is arrived by making two main assumptions: (i) the series resistance (being small) is neglected and (ii) the parallel resistance (being very large) is neglected.

From basic circuit laws the current through the load is obtained as

$$I_{L,PV} = I_{S,PV} - I_{o,PV}\left[e^{\left(\frac{eV_{PV}}{kT}\right)} - 1\right] \qquad (3.0)$$

Where $I_{S,PV}$ is the current in the solar cell that depends on the solar radiation (represented by the constant current source), 'e' is the electric charge ($1.6\text{X}10^{-19}$ Coulombs), k is the Boltzmann constant ($1.38 \text{ X } 10^{-23}$ J/K), T is the temperature in ^{o} Kelvin, $I_{o,PV}$ is the dark or saturation current and V_{PV} is the voltage across the junction.

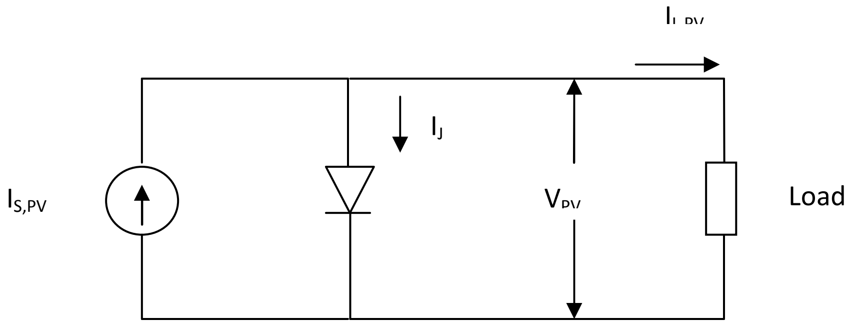


Fig. 3.1 Equivalent Circuit for the solar cell

A number of PV cells can be connected in series and parallel to increase the current and voltage rating. Such an arrangement is called a PV module. A solar panel may consist of many arrays consisting of many modules to get the required voltage and current. A standard panel identified by industry consists of 36 cell modules for large power production. The module is covered by tempered glass (or some other transparent material) on the front surface, and by a protective and waterproof material on the back surface. The whole arrangement is put in a weatherproof aluminum frame which can be mounted. The backside of the panel, there will be a junction box containing all the electrical connections.

Currently, four types of PV Modules are available:

MonoCrystalline

This type of solar module has the highest efficiency (15% to 20%) and is equipped with better sunlight conversion technology. The manufacturing cost of these modules is quite high.

Polycrystalline

The module efficiency in these modules is around 15%. But this type of module has a lower manufacturing cost.

StringRibbon

This type of solar module is a refined version of the polycrystalline structure. However, the costs are less. The modules have a cell efficiency of 12% to 13%.

Amorphous

This type of modules have a very low cell efficiency of 9% to 10% and the cost is also lower than the other types.

3.2 Performance of Solar PV modules.

The performance of the PV modules and arrays are generally rated according to the maximum DC power output under standard test conditions (STC),[Sharma, 2011] which are defined as Operating temperature of 25^{o}C and Incident solar radiation of 1000 W/sq.m. Since these conditions are not met always, the actual performance is about 87 – 92 % of the STC rating.

Due to improvement in technology, the PV modules available today are safe and quite reliable. They have a projected life span of 30 years and they have less failure rate. [www.oergon.gov, 2008]

The number of electrons dislodged by the sunlight in any PV system decides the amount of current. The number of these dislodged electrons is decided by the area of the cell, the efficiency of the cell and also by the incident solar insolation. The power of a PV cell is measured in peak kilowatts(kWp). This is the output of the cell when it is facing directly the sun on a very bright day during summer. Modern PV cells and modules are available in such a shape and size that they can be conveniently fitted on a rooftop.

In general, the larger the area of a module or array, the more the electricity, that will be produced. The power output of the module therefore depends on many factors such as the insolation, the area of the module, the materials used etc. With a large area available, PV can be used to generate power in bulk and can be integrated with the existing power distribution system. A typical power distribution system with solar PV powered embedded generation is shown in fig. 3.2.

Due to the high initial cost and requirement of considerable space, PV generation can be considered for Distributed Generation only, at the present scenario. However, it is expected that in the future, the entire energy will be derived from solar PV generation itself.

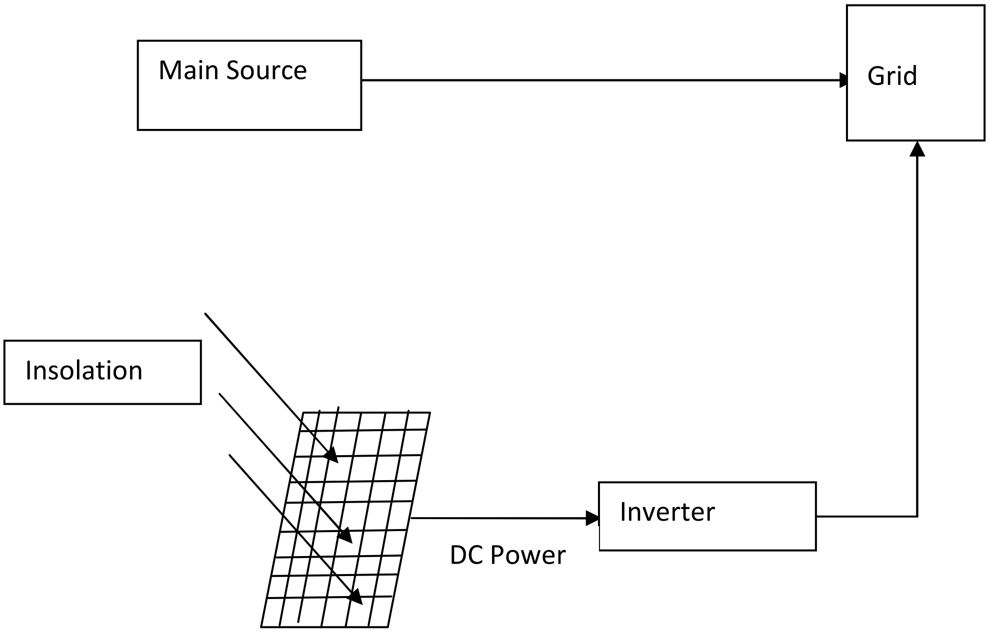


Fig. 3.2. Schematic showing the grid connection of solar pv generation

3.3 Modeling of PV generation.

The output of a PV system depends on several factors out of which insolation can be regarded as a prime factor. The modeling of the PV system therefore depends on the modeling of the insolation. Various models are available in the literature for modeling of the insolation such as the cloud model, probabilistic model, time series model and spectral model. [Yaramanoglu. et al. (1985)]. However, cloud cover modeling discussed in [Abouzahr.I and Ramkumar.R, 1993] has been accepted widely and is used here for analysis. Beta distribution is used to model the cloud cover.

Daylight hours of a day on any particular month, are divided into H time intervals, each interval being taken as one hour duration. Considering the jth time interval, the insolation at any time instant can be expressed in terms of the maximum possible value during that time interval.

$$i_j = I_{\max,j}(1-k_j) \tag{3.1}$$

Where i_j = insolation during jth time interval

$I_{max,j}$ = Maximum insolation during jth hour of the daylight.

k_j is a random variable representing the cloud cover during jth hour.

Since k_j varies between 0 and 1, the Beta distribution is more suitable. The probability density function for the cloud cover can then be expressed in terms of scale and size parameters as

$$f_{K_j}(k_j) = \frac{k_j^{\alpha_j - 1}(1-k_j)^{\beta_j - 1}\tau(\alpha_j + \beta_j)}{\tau(\alpha_j)\tau(\beta_j)} \tag{3.2}$$

Where $\tau(\alpha_j)$ and $\tau(\beta_j)$ are the gama functions and are given by

$$\tau(\alpha_j) = \int_0^{\infty} k_j^{\alpha_j - 1} e^{-k_j} dk \tag{3.3}$$

and

$$\tau(\beta_j) = \int_0^{\infty} k_j^{\beta_j - 1} e^{-k_j} dk \tag{3.4}$$

The parameters α and β are obtained by

$$\alpha = \mu\left[\frac{\mu(1-\mu)}{\sigma^2} - 1\right] \tag{3.5}$$

and

$$\beta = (1-\mu)\left[\frac{\mu(1-\mu)}{\sigma^2} - 1\right] \tag{3.6}$$

Where σ and μ are the variance and mean.

3.3.1 Modeling of PV Power Module

The factors that influence PV power output are effective area of cell modules, insolation, cell conversion efficiency and cell temperature. Neglecting cell temperature and assuming constant average cell efficiency, the PV output during j^{th} time interval, can be written as

$$P_{o,j} = A_{pv} K_p I_{\max,j} (1 - k_j) \eta$$

$$= P_{\max,j}(1 - k_j) \tag{3.7}$$

Where A_{pv} = Effective area of the cell

K_p = Packing factor

η = Efficiency

And $P_{max,j}$ is the maximum power output under clear sky conditions, during the j^{th} hour and is given by

$$P_{\max,j} = A_{PV} K_P I_{\max,j} \eta \tag{3.8}$$

The probability distribution function for the pv power output during j^{th} daytime interval, can be obtained, using transformation theorem as

$$f_{p_{O,j}}(p_{o,j}) = \frac{\tau(\alpha_j + \beta_j)}{\tau(\alpha_j)\tau(\beta_j)} \frac{1}{P_{\max,j}} \left(\frac{P_{o,j}}{P_{\max,j}} \right)^{\beta_j - 1} \left(1 - \frac{P_{o,j}}{P_{\max,j}} \right)^{\alpha_j - 1} \tag{3.9}$$

for $0 \le P_{o,j} \le P_{\max,j}$

3.3.2 Case Study

The Solar Power Generation for the city of Dharwad is considered as one of the DG resource. The details of evaluation of the electrical power generated from solar PV generation are discussed in this section.

In the present investigation, to make the analysis simpler, only the daytime intervals are considered and night durations are neglected. Since the meteorological measurement system is not available, the sunlight was measured using a lux meter from 6.00 AM to 6.00 PM for one year on all the days on hourly basis. The maximum insolation for the city of Dharwad was collected from [Ramachandra, 2007] and the same is used. The highest reading of the luxmeter was co related with this highest insolation in Dharwad. The variation of the sunlight for a typical day in a typical month is shown in fig 3.3. Using this data and noting that maximum sunlight occurs during the period between 1.00 PM and 2.00 PM, the probability density function is obtained. The probability density function of the cloud cover is shown in fig 3.4.

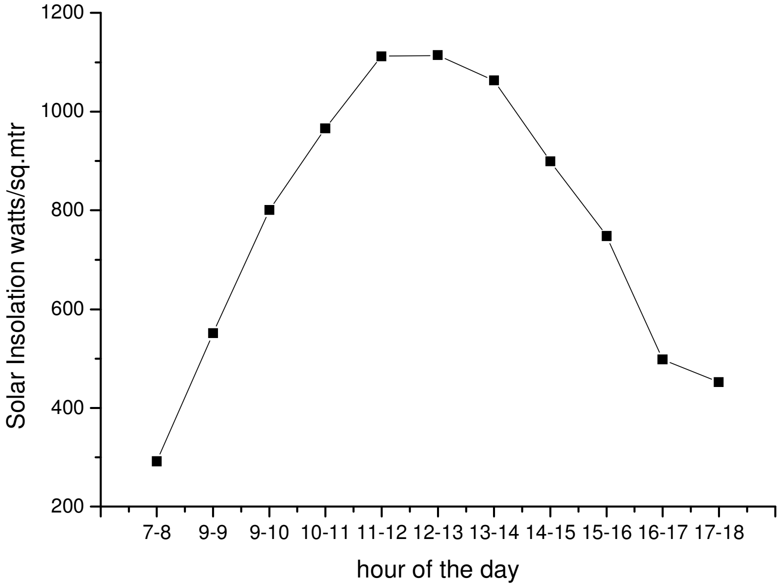


Fig. 3.3. Figure showing the typical variation of the solar insolation for one day

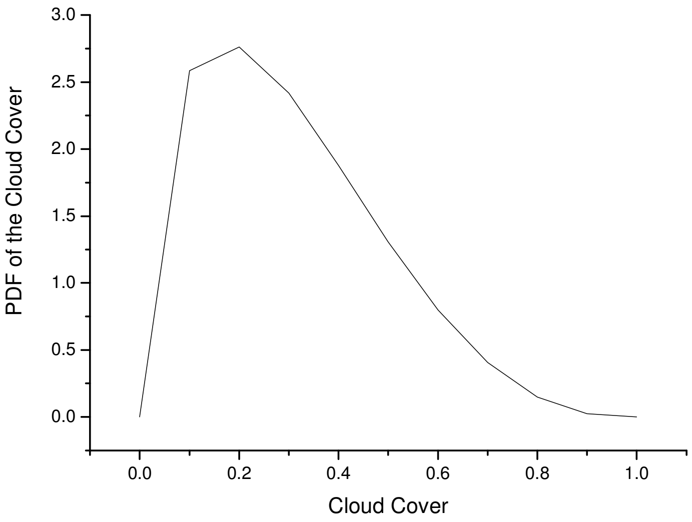


Fig 3.4. Figure showing the probability Density Function of the Cloud Cover

PV Power Output.

With the availability of information about the insolation, the next step was to find a suitable space for putting up the solar PV panels. Amongst many locations tried, one location was found to be more convenient. The location considered was the roof top space of a private- aided school which had no future plan of vertical construction. The roof top area on this building is 2028 sq.mtrs, out of which nearly 1650 sq.m can be used for solar PV generation.

With the above structural details required for PV generation, the PV output was estimated which turns out to be around 270 kWp taking poly crystalline modules into considerations.

From equation 3.8, we get the maximum output at the instant with maximum insolation (1112 w/sq.m) as

$$P_{max,j} = 1650 \text{ X } 1 \text{ X } 1112 \text{ X } 0.1475$$

$$= 270663 \text{ Watts} \qquad = 270 \text{ kW (approximately)}$$

Here, the packing factor is assumed as 1 and the efficiency of the PV module is taken as 14.75%

The probability density function for the PV module output is shown in fig 3.5. Though the maximum power calculated for a bright sunny day is 270 kW, during the other periods, the power output varies as it depends solely on the insolation. The site details are given in table 3.1 and the technical and other details of the proposed PV module system is shown in table 3.2. Table 3.3 gives the specifications of a sample module.

This small power plant is proposed to be connected to a feeder, namely UAS feeder, in Dharwad city as a DG unit.

The economic considerations of the PV generation are discussed in the next section.

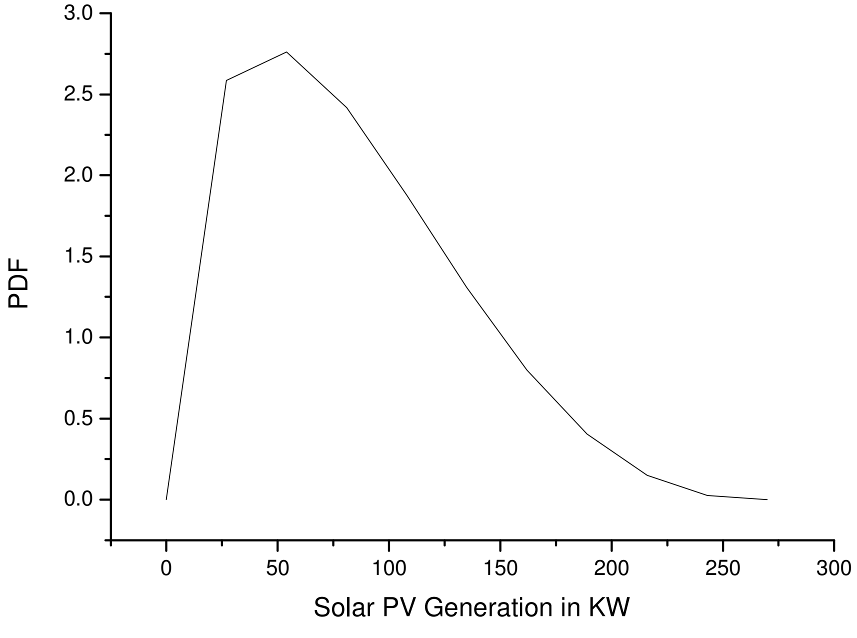


Fig 3.5. PDF of Solar PV Generation

Table 3.1. Geographical details of Dharwad city.

Latitude and Longitude	15.45^{o} N, 75.0^{o}E
Height above sea level	750 meters
Ambient air temperature	Max 41^{o}C, Min 15^{o}C
Rainfall	Annual average : 920 mm
Sunny days	320 (Approximately)

Table 3.2. Technical Data of Solar PV System.

Power rating of the module proposed	240 W_p
Total number of modules required	1125
Solar cell material	Mono – Crystalline Silicon
1 Array	24 Modules
Inverters	One of 270 kW
Number of arrays	47
Inclination of modules	15^{o}

Table 3.3. Sample Module specifications (Courtesy Titan Energy Systems Ltd)

Maximum Power Pmp (watts)	240
Maximum Power Voltage (Vmp)	29.62 Volts
Maximum Power Current (Imp)	8.12 Amps
Open Circuit Voltage (Voc)	37.62 V
Short Circuit Current (Isc)	8.55 Amps
Module Dimensions (mm)	1657 X 987 X 42
Number, Type & arrangement of Cells	60, Mono-Crystalline, 6 X 10 Matrix
Cell Size	156 X 156 (mm)
NOCT(NormalOperatingCell	45^{o}C
Weight	19 Kg
Glass Type and Thickness	3.2 mm thick, Low iron, Tempered

3.3.3 Economic Considerations:

The success of any project depends upon the performance and the economic viability of the project. The approximate economic details for the proposed PV plant are given in table 3.4.

Table 3.4. Estimated cost of the proposed power plant

Particulars	**Cost in Rs.**
SPV Arrays totaling to 270 kW	4,00,00,000
Inverters	50,00,000
Mounting Structures	30,00,000
Cables and Hardware	30,00,000
Junction Box and Distribution Boxes	5,00,000
Lightning Arresters, Earthing Kit etc	8,00,000
PVC pipes and accessories	1,50,000
Testing, Transportation and Insurance coverage etc	20,00,000
Erection and Commissioning	30,00,000
Taxes	1,00,000
Total	**5,75,50,000**

This estimation, however, does not include the miscellaneous charges, the royalty to be paid to the institution and the charges for safety measures to be adopted in the premises. The running cost will include the rent to be paid to the institution in addition to other usual maintenance expenditure. However, the royalty and the rent can be avoided if free space is available.

It is clear from the estimation that the estimation agrees with the prevailing cost of the energy generation using PV modules which is about Rs 2.00 Lac per kW installed capacity. Assuming that the city receives an average of 50 % of the maximum insolation for about 10 hours on any bright day without rainfall, the total energy generated per day will be 270 X 0.5 i.e. 135 kW.

If there are 320 such days then the annual energy generated will be 135 X 10 X 320 which turns out to be 4,32,000 kWh. If this energy is supplied to the grid, the revenue earned based on the normal tariff (Rs.5.00/- per kWh) is Rs.21,60,000/-

Mathematically, the payback period is 28 years. However, the installation of the DG unit gives a confidence of sustained availability of electrical energy and cannot be evaluated in terms of payback or returns, etc. This can also be taken as a joint venture of both HESCOM and HDMC both of which ultimately will earn goodwill of the public.

3.4 MSW Derived Power Generation

The disposal of waste has been a serious problem in all the countries with the amount of waste tending to increase due to increased population and increased industrialization. Waste disposal is also an environmental issue in many nations due to densely urbanized cities. India is also not an exception. It is estimated that waste is generated at the rate of nearly 0.5 Kg per person per day [Ranade, Bapat, 2011]. The present practice of open dumping the waste cannot be continued in the future because the availability space for open dumping cannot be taken for granted forever. Under such circumstances, a very useful Solid Waste Management method has to be adopted for efficient waste disposal.

It is already proved that by incineration of MSW yields electrical energy. This method therefore provides an effective waste disposal method in addition to the power generation.

3.4.1 Suitability of MSW for Incineration:

The next step is to find whether the MSW of the city is suitable for incineration. MSW is a nonhomogeneous fuel that differs greatly from conventional fossil fuel. The physical and chemical parameters of the MSW decide whether the waste will sustain the combustion without the need of any supplementary fuel or not.

The sample of waste to be incinerated is fist tested for the percentage contents of moisture, ash and combustible parts. Values of Ash content A, Combustible content C and Moisture W can be obtained by burning the known weight of the sample and measuring the ash content and the moisture content. The results are then plotted in Tanner’s triangle diagram[Rand, T., et al. (2000)]. shown in fig 3.6, to confirm whether it falls within the shaded area indicating a combustible fuel. The waste is theoretically feasible for combustion without auxiliary fuel when

% $W_W < 50$; $A_W < 60$ and $C_W > 25$.

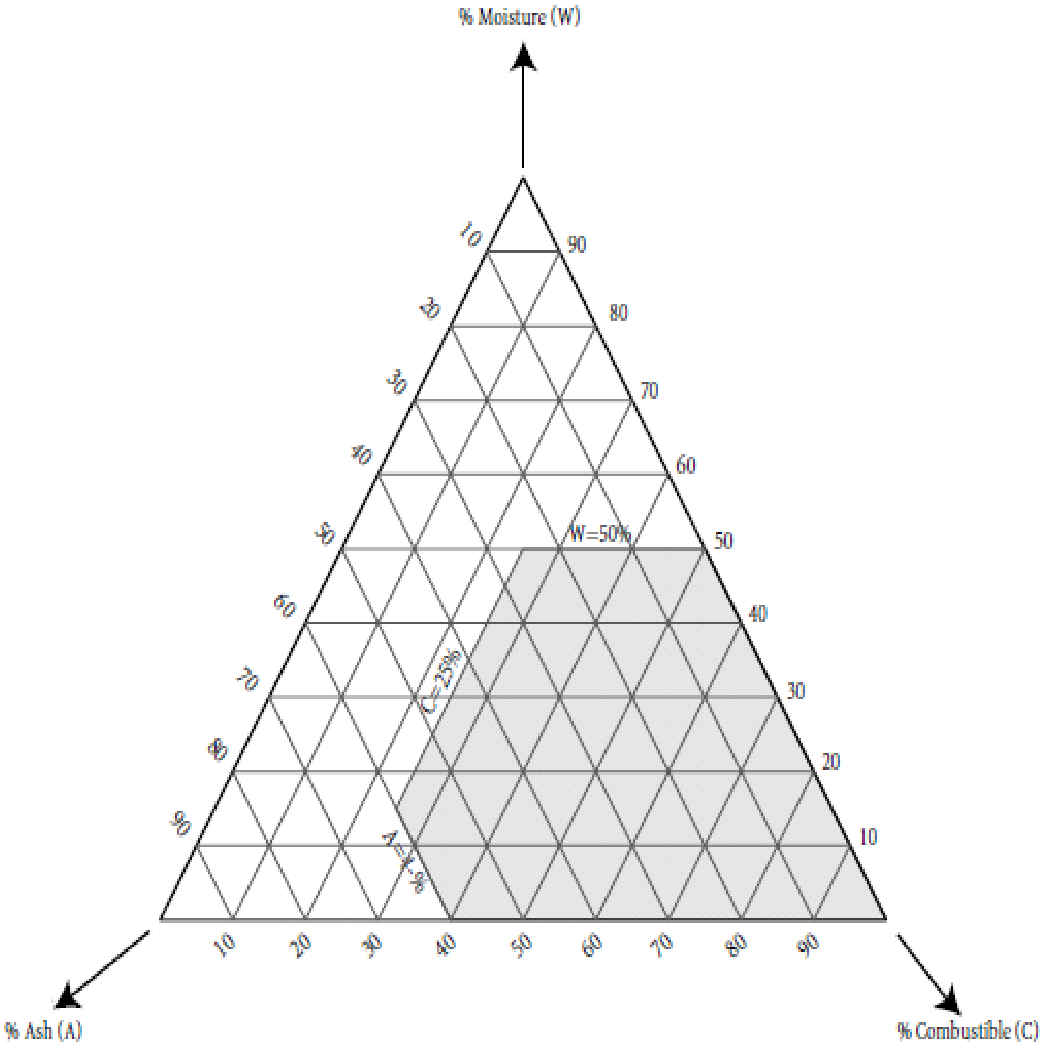


Fig. 3.6 Tanner's triangle

The Calorific Value (CV) of the sample is estimated by the following equation.

$$CV_{overall} = \frac{M_1}{100} \times CV_1 + \frac{M_2}{100} \times CV_2 + ... + \frac{M_n}{100} \times CV_n \qquad (3.10)$$

Where CV$_1$, CV$_2$ …….. are the calorific values of the constituent components of the waste and M$_1$, M$_2$,…… are the weights of these components on dry basis. Table 3.5 gives the typical values of % moisture, % ash , % combustible portions and the CVs of various components.

Table 3.5 Table showing the Moisture, Ash, combustible portion contents and the Heat value of waste components.

Waste	Moisture	Ash	Combustible	Calorific Value (Kwh/Kg)
Food Waste	70	13	17	1.292
Plastics	29	7.8	63.2	9.044
Textiles	33	4.0	63	5.55
Paper &	47	5.6	47.4	4.65
Leather &	11	25.8	63.3	6.39
Wood	35	5.2	59.8	4.75
Metals	6	94	0.0	---
Glass	3	97	0.0	---
Yard Trimmings	65	10	35	1.826

If the CV so arrived is more than the standard value of 4500 kWh/Kg, then the MSW is suitable for incineration without any supplementary fuel.

The MSW is then burnt in the incinerator which gives out steam. The steam generated is then used to run a steam turbine which in turn rotates an alternator producing electricity. The amount of electricity so generated, depends on the efficiencies of both the incinerator, steam turbine and the alternator. A typical MSW Combustion plant, [Aerne, et al. (2002)] is shown in fig 3.7

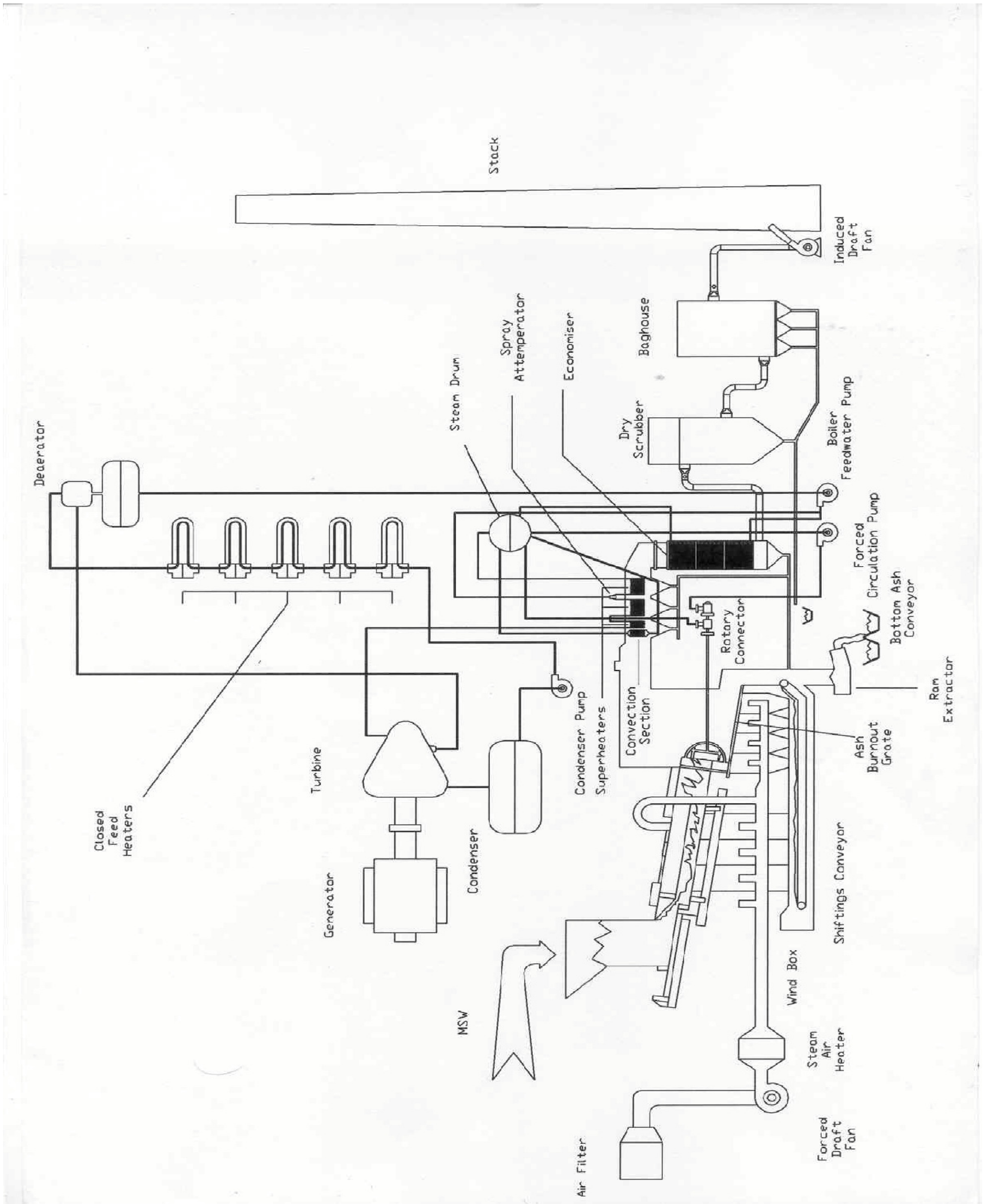


Fig 3.7 A typical MSW Combustion Plan (Courtesy P. Aarne Vesiland, Willium Worrell, Debra Reinhart,(2002), " Solid Waste Engineering", Cengage Learning India Private Limited.)

3.4.2 Case Study.

The city of Dharwad, divided in 22 wards, produce nearly 200 tonnes of waste every day. An area of 15 acres of land is used currently for dumping this waste. Already this has given rise to many environmental, social and operational problems. The issues are going to be further alleviated because soon the dump yard will be filled up and a new site has to be located. However, this cannot continue forever because after some more years, the space for landfill may not exist.

Out of the total waste generated, nearly 150 tonnes of waste is collected and is disposed in the form of open dumping. Though the recycling process is in operation, it hardly reduces the amount of waste that is dumped openly. The Waste is collected is transported to the final destination i.e. open dumping everyday through tractors.

To check the suitability of the waste for power generation, waste samples were collected for six months on a daily basis and the composition of the waste was studied. The details of the average composition of waste are given in table 3.6.

Table 3.6 : Average Composition of daily waste collected.

Component	**Wet waste** (Kitchen+Veg+Flower)	**Plastic+Textile+ Rubber**	**Dry waste** (Paper+ cardboard + wood)	Soil, building waste including glass and metals
% of Weight	25.2	4.3	13.7	56.8

The waste sample was then tested in a Bomb Calorimeter which gave an average calorific value of 4436 cal/gram. Since the measured value of the CV is very close to the standard value of 4500 cal/gm,[Aarne, et al (2002)] the waste could be used as fuel for power generation. The average values of moisture, ash and combustible contents were also recorded and are :- Ash – 46%; Combustible – 58% and Moisture – 54%.

When plotted on Tanner’s triangle, the position was very close to the shaded portion. Hence it was considered fit to be used as a fuel for power generation.

After deducting the moisture contents from each of the components, the weights of the dry components which can be used for combustion were calculated and are shown in table 3.7.

Table 3.7. Table showing the dry components of the waste.

Component weight	**Wet waste** (Kitchen+Veg+Flower)	**Plastic+Textile+ Rubber**	**Dry waste** (Paper+ cardboard + wood)
As % of Total Weight on dry basis	8.54	3.12	7.17
As % of the dry waste weight	40.3	15.8	36.2

The exact calorific value of the sample is then obtained by substituting the weight of the components as a % of the dry waste and by knowing the corresponding calorific value from table 3.5

$$CV = 0.403 \times 1.292 + 0.158 \times 9.044 + 0.362 \times 4.65$$

$$= 3.6329 \text{ kWh/Kg} = 3632.9 \text{ kWh/Tonne}$$

The net weight of the waste collected for incineration is 18.83 tonnes/day, on a dry basis. Multiplying this by the CV, the net energy available for conversion is calculated which is 68407 kWh.

Assuming the efficiency of incinerator, steam turbine and the alternator as 65%, 60% and 85% respectively, the total electrical energy which can be generated will be 19930 kWh/day

It is therefore possible to install an alternator of a rating of 800 kW.

3.4.3 Economic Considerations.

A model for estimating the operating cost of the plant is proposed in this investigation. The working of the plant and the process is quite complex and many factors have to be taken into account. The following processes are to be considered for model development. These essential features are

- Collection of the waste at the doorstep and the streets by the collection crew.
- Transportation of the waste so collected to a community dustbin (CDB) placed in an area
- Collection of the waste from the CDB at regular intervals and transportation of the same to a Depot where the waste are separated.
- First level of separation of the waste in to
    - Wet waste including Kitchen & vegetable waste
    - Plastics + Textile + Rubber
    - Paper +Cardboard + wood
    - Soil & building waste including Glass and metals
- Second level separation of the waste in to compostible, noncompostible, recyclable, non recyclable, combustible, non combustible.
- Transportation of waste to the final process
- Incineration of the waste resulting into steam.
- A steam turbine running a generator

For each of these activities, there are a number of alternatives. For example, there are several separation processes depending upon the type of waste that is collected. The waste collected has to pass through several processes before it is declared fit to be incinerated for power generation .e.g. after recovering the recyclable content from a waste, only the high heat content of the remaining, should be sent to incineration.

Thus a number of waste flow paths can be identified and each path can be modeled by means of a mathematical equation. The modeling of MSW for various processes is thus, very complex and was presented in [Eric Solano,2002]. The concept of MSW Fuelled Power Generation (MSWFPG) for India was presented in [Palanichamy., et al. (2002)]. However, the cost estimation for the entire process of power generation in India has not been obtained earlier.

3.4.4 Model Formation

Figure 3.8 gives the details of various processes that a waste undergoes from collection at doorstep till the final disposal. From the figure, FOUR major waste flow alternatives are defined, depending on the final process. They are

- Waste to Incineration A_1 - $(C_0 – P_1)$
- Waste to Recycle Plant A_2 - $(C_0 – P_2)$
- Waste to Compost Yard A_3 - $(C_0 – P_3)$
- Waste to DumpYard A_4 – $(C_0 – P_4)$
- These major waste flow alternatives can be further subdivided into a number of alternatives e.g the waste that is incinerated can be from (i) the noncompostible kitchen waste after drying, (ii) the other dry Waste which is nonrecyclable and combustible and (iii) plastic which is nonrecyclable. Table 2 gives all these various flows

A variable is defined that represents the mass of the waste that flows in a particular mass flow alternative.

$x(A_1)$, $x(A_2)$, $x(A_3)$ and $x(A_4)$ represents the total mass of the waste in tons / year that follows paths A_1, A_2, A_3 and A_4 respectively.

The mass balance equation is then written as

$$x(A_1) + x(A_2) + x(A_3) + x(A_4) = M_{waste} \qquad (3.11)$$

where M_{waste} is the total waste collected in tons/day

Table 3.8 gives the details of various processes that a waste undergoes from the collection after the separation at the doorstep till the final disposal

The mass entering a final process can be from various unit processes. e.g. the mass that is incinerated can be either from the path E_{11} , E_{12} E_{13} or E_{14}.These waste flow paths for the final processes are given in table 2. The mass balance equation for the mass that is incinerated alone is then written as

$$x(A_1) = x(A_1, E_{11}) + x(A_1, E_{12}) + x(A_1,E_{13}) + x(A_1, E1_4) \quad (3.12)$$

Similarly the mass balance equations for other processes can be written as

$$x(A_2) = x(A_2, F_{11}) \quad (3.13)$$

$$x(A_3) = x(A_3, G_{11}) \quad (3.14)$$

$$x(A_4) = x(A_4, H_{11}) \quad (3.15)$$

These linear equations give the feasible mass flows of waste through the entire SWM system.

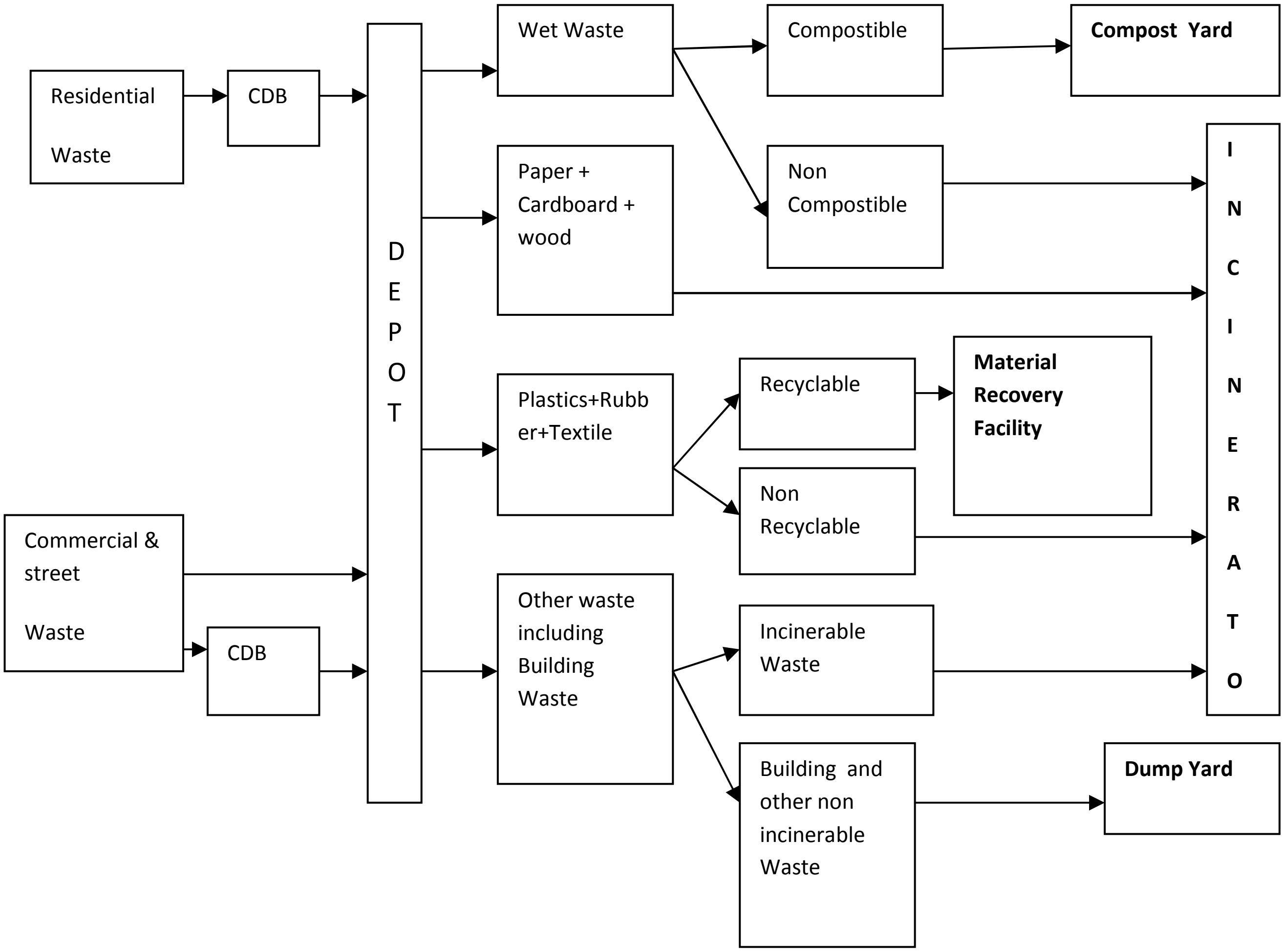


Fig.3.8 : Figure showing the various waste flow paths

Table 3.8 (a) Unit Processes for Waste Management Activities: Collection ;(b) Unit Processes for Waste Management Activities: Separation; (c) Unit Processes for Waste Management Activities: Transportation and (d) Unit Processes for Waste Management Activities: Final treatment

(a) **Unit Process : Collection**		Collection of Building & other non incinerable Waste after separation and transportation to Dump Yard	C62
Collection of Residential waste at doorstep and transportation to CDB	C0		
Collection of street + Building waste and Transportation to Depot	C1	**(b) Unit Process : Separation**	
Collection of Commercial waste at doorstep and transportation to CDB	C2	Separation of mixed waste into (i) Wet Waste, (ii) Paper+Cardboard + Wood, (iii) Plastics +Rubber+Textile and (iv) Building + other dry	S1
Collection of Residential waste from CDB and Transportation to Depot	C01	Separation of wet waste into compostable and Non compostible	S12
Collection of Commercial waste from CDB and Transportation to Depot	C21	Separation of Plastics + Rubber + Textile into recyclable/Nonrecyclable	S13
Collection of Compostible Waste after separation and Transportation to Compost Yard	C31		
Collection of Non Compostible Waste after separation and Transportation to Incinerator	C32	**(d) Unit Process : Final Disposal**	
Collection of Platics+wood+cardboard after separation and transportation to Incinerator	C4	Incineration	P1
Collection of recyclable plastics+rubber+textiles after separation and transportation to Material Recovery Facility	C51	Composting	P2
Collection of non recyclable plastics+rubber+textiles after separation and transportation to Incinerator	C52	Material Recovery	P3
Collection of other incinerable dry waste after separation and transportation to Incinerator	C61	Open Dumping	P4

Table 3.9 : Table showing the waste flow paths

Waste Flow alternative	Path Followed
E_{11}	C – S1 – S11 – C32 – P1
E_{12}	C – S1 – C4 – P1
E_{13}	C – S1 – S12 – C52 – P1
E_{14}	C – S1 – S13 – C61 – P1
F_{11}	C – S1 – S11 – C31 – P2
G_{11}	C – S1 – S12 – C51 – P3
H_{11}	C – S1 – S13 – C62 – P4

The objective function for MSWFPG can be either the cost function or the environmental factor. Choosing the cost function, the objective function is then to

Minimize Cost_U

Where U = $C \cup S \cup P$, the set of all unit processes.

Hence $\text{Cost}_U = \sum_{k \in O} \alpha_{u,k} x_{u,k}$ (3.16)

Where $\alpha_{u,k}$ = cost coefficient for processing waste item ‘k’ at unit the process ‘u’ in Rs./ton.,

$x_{u,k}$ = mass of waste item ‘k’ processed by unit process u tons/year and

O = set which includes all the items.

Considering Incineration alone, equation (3.16) can be rewritten as

$\text{Cost}_u = \alpha_{11}x(A_1, E_{11}) + \alpha_{12}\, x(A_1, E_{12}) + \alpha_{13}\, x(A_1,E_{13}) + \alpha_{14}x(A_1,E_{14})$ (3.17)

Subject to the constraints

$x(A_1, E_{11}) + x(A_1, E_{12}) + x(A_1,E_{13}) \geq B_0$;

$x(A_1, E_{11}) \geq B_1$;

$x(A_1, E_{12}) \geq B_2$

$x(A_1, E_{13}) \geq B_3$;

$x(A_1, E_{14}) \geq B_4$

Where

α_{11} = the cost coefficient for processing the waste in the path E_{11}

α_{12} = the cost coefficient for processing the waste in the path E_{12}

α_{13}= the cost coefficient for processing the waste in the path E_{13}

α_{14}= the cost coefficient for processing the waste in the path E_{14}

The values B_0,B_1,B_2 B_3 and B_4 represents the average quantity of waste collected in the respective categories and are evaluated taking the past details of the waste collected and keeping in view, the change in the trend of the waste collected. The cost coefficients α_{11} , α_{12} , α_{13} & α_{14} are evaluated taking the cost of labor for corresponding processes only. Similarly the cost functions for the other waste flow paths are obtained. The equations so obtained are solved for the optimum performance of the plant.

Cost considerations made towards various processes are shown in table 3.10

Table 3.10 : Cost consideration of various processes.

Process	**Wage/employee/day**
Door to door collection	Rs. 50
Waste collection from	Rs. 40
Separation of waste into	Rs. 150
Collection from	Rs. 40
Incineration of waste	Rs. 250

Considering only the labor charges and the fuel charges for MSW handling and transportation , the cost coefficients for various processes are arrived at

α_{11} = Rs.380.64 per ton of waste.

α_{12} = Rs. 368.5 Per ton of waste.

α_{13} = Rs. 478.5 Per ton of waste.

α_{14} = Rs. 370.8 Per ton of waste.

The equation is therefore, to minimize

$$Cost_U = 380.64\ x(A_1, E_{11}) + 368.5\ x(A_1, E_{12}) + 478.5\ x(A_1, E_{13}) + 370.8\ x(A_1, E_{14}) \tag{3.18}$$

Subject to constraints

$$x(A_1, E_{11}) + x(A_1, E_{12}) + x(A_1,E_{13}) \geq 34.14$$

$$x(A_1, E_{11}) \geq 2.259$$

$$x(A_1, E_{12}) \geq 2.52$$

$$x(A_1, E_{13}) \geq 10.08$$

$$x(A_1, E_{14}) \geq 5.2$$

The values of B_0, B_1, B_2 and B_3 were arrived at after collecting samples of MSW of all the wards of Dharwad city for six months and determining the calorific values of the respective wastes in the laboratory for their suitability for incineration.

Solving the above equations, the following results were obtained.

Optimal solution – Rs. 53733 /ton

Since the total weight of waste that is collected and processed for incineration is 34.14 tons, the total cost of the process turns out to be Rs 18,34,445/day. From the earlier estimation, the energy generated per day is 19930 kWh.

In this process, the capital investment is not considered. Certainly the cost of energy produced from this process is very high. It is also true that similar processes are available elsewhere in the world. However, the waste composition in India differs from that in other countries mainly in its calorific value. Hence the cost is high. However, the cost can be minimized by adopting following measures

i. Separating the waste at the point of generation.
ii. Increasing the number of depots so that transportation cost can be reduced.
iii. Using the same labors for different jobs.

This DG unit is proposed to be connected to the selected UAS feeder of Dharwad City. The distribution network of the city is shown in Fig. 3.9

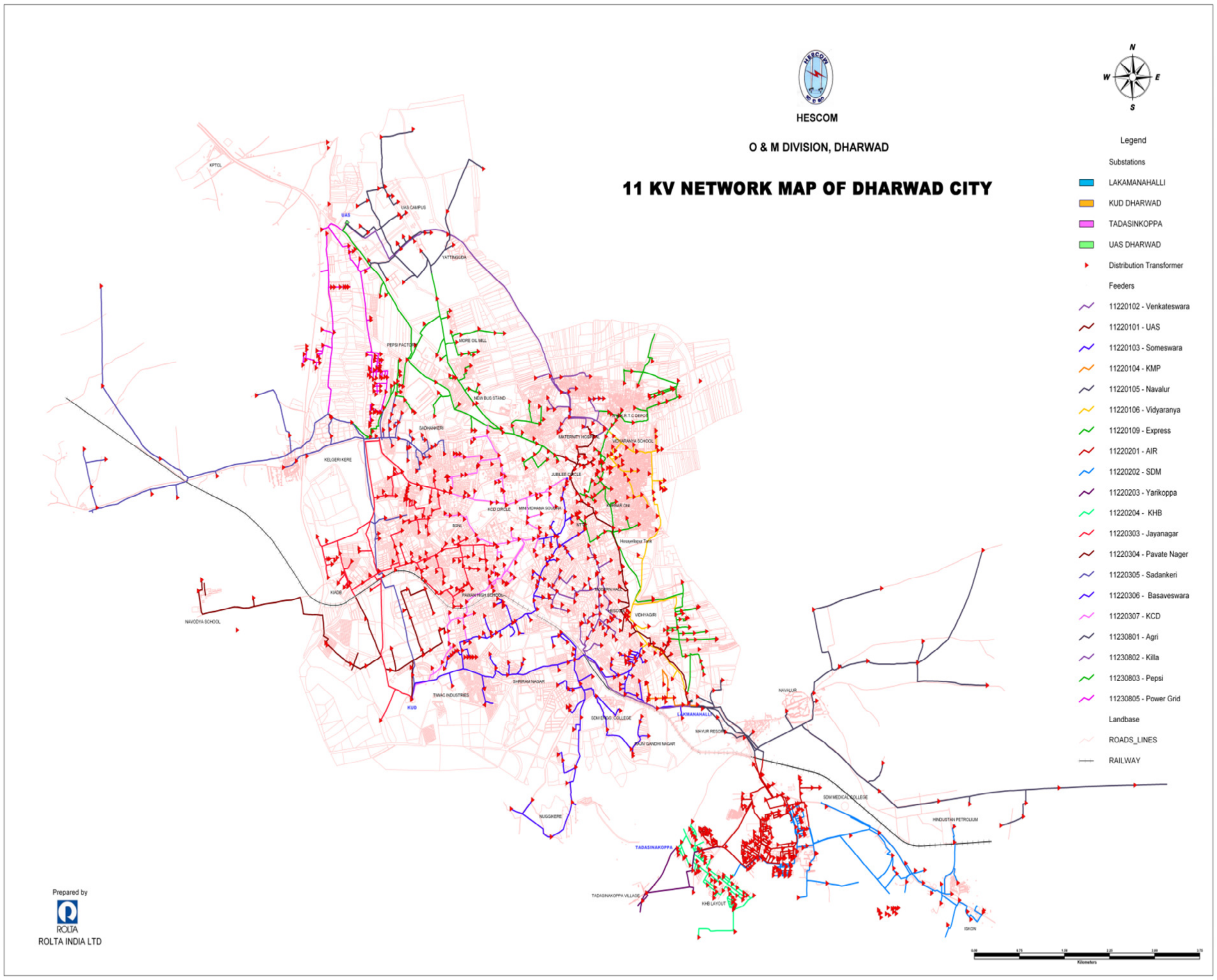


Fig. 3.9 11 KV network of Dharwad City.

3.4.6 Emission Issues related to MSWFPG

The derivatives of the incineration process of MSW needs special attention because of their characteristics. Usually the combustion reduces the weight of the substance by 75% and the volume by 90%, leaving a good quantity of inert ash(60% of the burnout weight distribution) and fly ash in a percentage rate of 40% of the burnout weight distribution.[N.D.Strachan, 2000] 3% of the inert ash consists ferrous material can removed by a system employing magnets before the inert ash is deposited in a specified collection area. This portion of inert ash can be collected regularly and sold as a first class fertilizer to interested industries later on. The portion of the fly ash that is generated from the mass burning combustion has a code of handling and storing that is more complicated because of its constituent products: Nitrogen Oxides (NOx), Sulphur Oxides (SOx), Particulate Matter (PM), Carbon Monoxide (CO), Carbon Dioxide (CO2) as well as HCL, dioxins/furans, heavy metals and organic constituents create a mixture that is hazardous for the environment as well as for public health if released into the atmosphere unprocessed[A J Chandler et al. (1997)]. Hence the plant should take proper measures to deal with these emissions and strictly adhere to all the legislative standards so that public health is not affected while maintaining the environmental sustainability.

CHAPTER 4

PROPOSED QUANTIFICATION OF THE BENEFITS OF DISTRIBUTED GENERATION.

The inclusion of DG in the power distribution network has great impacts on the issues like line losses, voltage profile, reliability, protection, etc. The impacts will be more pronounced with higher penetration of DG. The positive impacts of DG are the reduced line losses, improvement in voltage profile, greater reliability, deferral of investment, etc. However, it is also true that with large penetration, these impacts may become negative, causing adverse effect on the performance of the system. It becomes therefore, essential to evaluate the impacts of DG units on the performance of the distribution network and quantify them.

In this chapter, two issues have been considered- effect of DG on (1) line loss reduction and (2) voltage profile improvement. With regard to the first issue, an index, quantifying the system line loss reduction has been proposed. With respect to the second issue, the voltage profile of the system with DG has been studied with different locations and ratings of DG and a very simple index quantifying the improvement is proposed. Both the indices are evaluated for a test system and are recorded

4.1 System Loss Reduction

The losses in a distribution system include the line losses both on HV & LV sides and the core losses in the transformers. Line losses are those losses that occur in the lines and therefore depend upon the line resistance and the current flowing through the line. The magnitude of this loss will therefore be more under heavy load conditions. On the other hand, the core losses of the transformers remain constant and will occur irrespective of the load magnitude. The utility will then be forced to pass these losses to all the customers to recover the cost. It would be beneficial to find means to reduce these losses so that both the utility and the customers are benefitted. The inclusion of DG has been found to reduce the line losses among many other benefits. By inserting a DG unit, line currents in some sections of the line are reduced and hence the loss reduction takes place. Most of the earlier investigations were focused on the reduction of line losses on the HV side only and did not consider the losses in the transformers and the losses on the low voltage side. A practical distribution system consists of a number of distribution transformers, the low voltage side of which supply power to a majority of the customers. The losses of the transformers and the losses on the LV side play a dominant role in deciding the total losses. Hence, these losses should also be considered while evaluating the benefits of DG for the distribution system in general.

Consider a feeder delivering power to consumers through a number of distribution transformers. The schematic is shown in fig 4.1. The line is divided into a number of segments and at the end of each, a distribution transformer is connected. Customer loads are connected to the low voltage side of the distribution transformers. For simplicity, the following assumptions are made

- The core losses of the transformers remain constant at a value depending on the rating.
- DG2 is capable of supplying power at both leading and lagging power factors

The total loss of the distribution system is given by

$$P_{Loss} = \sum_{i=1}^{N-1} I_i^2 \, r l_i + \sum_{i=1}^{N-1} \left(P_{C_i} + P_{LV_i}\right) \tag{4.1}$$

Where I_i is the current flowing through ith segment

l_i is the length of ith segment

r is the resistance of line in ohms per unit length.

P_{C_i} is the core loss of ith transformer

P_{LV_i} is the Losses on the low voltage side of the ith transformer.

N is the number of busses in the system.

In order to determine the losses of the system, current distribution, the core loss of each transformer and the LV side losses on each transformer must be known. It is evident from the above equation that the total losses can be reduced only by reducing the first term of the equation (4.1) which represents the feeder line losses, since the other term representing the core loss and the LV side loss of each transformer remain same independent of the presence of DG.

With the inclusion of DG, the currents in the feeder segments will be redistributed. The evaluation of the redistribution of the current depends upon the load model selected. Three common types of load models are available in the literature and they are:

- Constant Current model
- Constant Impedance Model
- Constant Power Model

Alternatively, ZIP model can also be employed. The next section describes the evaluation of the branch currents using the constant current load model and the constant impedance load models.

Case A: *Constant Current model:*

In this case, all the loads are modeled as constant current models, carrying the same current, irrespective of the terminal voltages. The basic equation describing this model is

$$\frac{P}{P_O} = \left(\frac{V}{V_O}\right) \qquad (4.2)$$

where P is the power drawn by the load at a voltage V & P_O and V_O are the initial values of power and voltage respectively.

If a DG unit is inserted at Kth bus, all the feeder segments up to bus K will carry the difference between the initial current and the injected current by the DG unit. The segments beyond K will continue to carry the same currents. The total loss of the feeder with DG is the given by

$$\text{Loss}_{\text{Feed w DG}} = \sum_{i=1}^{K-1}(I_i - I_G)^2\, rl_i + \sum_{i=K}^{N-1} I_i^2\, rl_i \qquad (4.3)$$

Where I_G is the current injected by the DG unit and I_i remains the same at earlier value.

The total loss of the distribution system with DG is now

$$\text{Loss}_{\text{Syst w DG}} = \sum_{i=1}^{K-1}(I_i - I_G)^2\, rl_i + \sum_{i=K}^{N-1} I_i^2\, rl_i + \sum_{i=1}^{N-1}\left(P_{C_i} + P_{LV_i}\right) \qquad (4.4)$$

This equation can be rewritten as

$$\text{Loss}_{\text{Syst w DG}} = \sum_{i=1}^{K-1}(I_i^2 - 2I_iI_G + I_G^2)\, rl_i + \sum_{i=K}^{N-1} I_i^2\, rl_i + \sum_{i=1}^{N-1}\left(P_{C_i} + P_{LV_i}\right) \quad (4.5)$$

$$= \sum_{i=1}^{N-1} I_i^2\, rl_i + \sum_{i=1}^{K-1}(I_G^2 - 2I_iI_G)\, rl_i + \sum_{i=1}^{N-1}\left(P_{C_i} + P_{LV_i}\right) \qquad (4.6)$$

Substituting equation (4.1) in equation (4.6) we get

$$\text{Loss}_{\text{Syst w DG}} = \text{Loss}_{\text{Syst w/o DG}} + \sum_{i=1}^{K-1}(I_G^2 - 2I_iI_G)\, rl_i \qquad (4.7)$$

On simplification following equation is obtained

$$\text{Loss}_{\text{Syst w DG}} = \text{Loss}_{\text{Syst w/o DG}} + \sum_{i=1}^{K-1} I_G(I_G - 2I_i)\, rl_i$$

$$= \text{Loss}_{\text{Syst w/o DG}} + K_{\text{loss}}\, I_G \qquad (4.8)$$

Where K_{loss} is the loss factor given by $K_{\text{loss}} = \sum_{i=1}^{K-1}(I_G - 2I_i)\, rl_i$ (4.9)

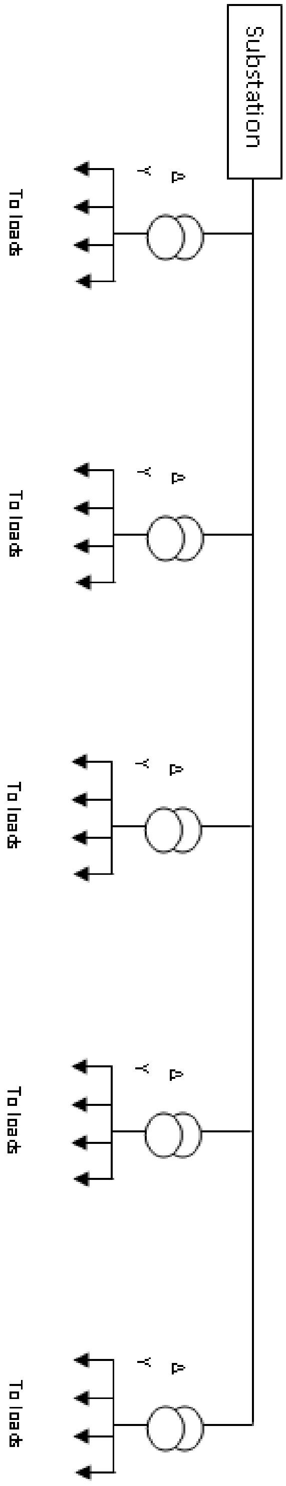


Fig 4.1 A typical distribution system.

CASE B: *Distribution system with Constant Impedance load model*

In this case the load impedance is independent of the connection voltage and the expression for power P drawn by a load at a voltage V is given by

$$\frac{P}{P_O} = \left(\frac{V}{V_O}\right)^2 \qquad (4.10)$$

where P_O and V_O are the initial values of power and voltage respectively.

The network equation with N nodes with node 1 as the input node, can be written as

$$\begin{bmatrix} Y_T & Y_U \\ Y_U^T & Y_{\ W} \end{bmatrix} \begin{bmatrix} V_1 \\ V_L \end{bmatrix} = \begin{bmatrix} I_1 \\ I_L \end{bmatrix} \qquad (4.11)$$

Where Y_U, Y_T and Y_W are the sub-matrices of the admittance matrix of the system and V_L and I_L are the voltage and the injected currents at nodes 2 to N.

With the constant voltage V1 at bus 1 and the injected currents from node 2 to N being zero, the voltages at all the buses from 2 to N are given by

$$V_L = -Y_W^{-1}\, Y_U^T\, V_1 \qquad (4.12)$$

Hence the current flowing through a branch I is

$$I_i = \left(V_{i_a} - V_{i_b}\right) Y_i \qquad (4.13)$$

Where V_{ia} and V_{ib} are the voltages at the sending end and receiving ends of the branch and Y_i is the admittance of the branch i.

The total loss of the distribution system without DG is given by

$$\text{Loss}_{\text{Syst w/o DG}} = \sum_{i=1}^{N-1} I_i^2\, rl_i + \sum_{i=1}^{N-1}\left(P_{C_i} + P_{LV_i}\right) \qquad (4.14)$$

With the same notations as used earlier.

The inclusion of a DG is considered by assuming an extra bus N+1, which connects the DG to a local load bus. The network equation with DG is given as

$$\begin{bmatrix} Y_T & Y_U & Y_V \\ Y_U^T & Y_W & Y_Z \\ Y_V^T & Y_Z^T & Y_X \end{bmatrix} \begin{bmatrix} \Delta I_1 \\ \Delta V_L \\ \Delta V_{DG} \end{bmatrix} = \begin{bmatrix} \Delta I_1 \\ \Delta I_L \\ \Delta I_G \end{bmatrix} \tag{4.15}$$

Where

$Y_V = \left[Y_{1,N+1}\right]$ *and* $Y_X =$

$\left[Y_{N+1,N+1}\right]$ *and* V_{DG} *is the voltage at the DG terminal.*

$$Y_Z = \begin{bmatrix} Y_{2,N+1} \\ \vdots \\ Y_{N,N+1} \end{bmatrix}; \qquad \Delta V_L = \begin{bmatrix} \Delta V_2 \\ \vdots \\ \Delta V_N \end{bmatrix} \ and \ \ \Delta I_L = \begin{bmatrix} I_2 \\ \vdots \\ I_N \end{bmatrix} \tag{4.16}$$

Since the buses 2 to N are considered to be the loads, there is no current injections into bus 2 to N. Also considering the voltage at the input bus 1 do not change, the voltage changes from bus 2 to N due to the current injection from the DG are

$$\Delta V_L = -Y_W^{-1} Y_Z (Y_X - Y_Z^T Y_W^{-1} Y_Z)^{-1} \Delta \mathrm{I_G} \tag{4.17}$$

Substituting $\Delta I_G = I_G$, equation 4.16 is modified as

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_N \end{bmatrix} = \begin{bmatrix} 0 \\ a_2 + jb_2 \\ \vdots \\ a_N + jb_N \end{bmatrix} I_G \tag{4.18}$$

Where a_i and b_i are the elements of the coefficient matrix.

The new values of the bus voltages are obtained by combining the initial voltages and equation 4.17 and are given by

$$\begin{bmatrix} V_1^{DG} \\ V_2^{DG} \\ \vdots \\ V_N^{DG} \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} + \begin{bmatrix} 0 \\ a_2 + jb_2 \\ \vdots \\ a_N + jb_N \end{bmatrix} I_G \tag{4.19}$$

Hence the current flowing through a branch *i* is

$$I_i^{DG} = \left(V_{i_a}^{DG} - V_{i_b}^{DG}\right)Y_i \tag{4.20}$$

$$= \left\{\left[V_{i_a} + (a_i + jb_i)I_G\right] - \left[\left[V_{i_b} + \left(a_f + jb_f\right)I_G\right]\right]\right\}Y_i \tag{4.21}$$

Where V_{ia} and V_{ib} are the voltages at the sending end and receiving ends of the branch and Y_i is the admittance of the branch i.

Equation (4.21) can be simplified as

$$I_i^{DG} = \left[\left(V_{i_a} - V_{i_b}\right) + (A_i + jB_i)I_G\right]Y_i \tag{4.22}$$

Where $A_i = a_i - a_f \quad and \quad B_i = b_i - b_f$

The copper losses in the ith segment of the feeder are estimated as

$$Loss_{feed,i} = I_i^{DG^2}\, r\, l_i = \left[\left(V_{i_a} - V_{i_b}\right) + (A_i + jB_i)I_G\right]^2 Y_i^2 r l_i \tag{4.23}$$

On neglecting higher order terms and simplifying, we get

$$I_i^{DG^2}\, r\, l_i = \left(V_{i_a} - V_{i_b}\right)^2 Y_i^2 r l_i + K'_{Loss} I_G \tag{4.24}$$

Where

$$K'_{Loss} = 2\left(V_{i_a} - V_{i_b}\right)(A_i + B_i)Y_i^2 r l_i$$

Combining equation (4.1), (4.14) and (4.24), the total loss of the feeder with DG is given by

$$\text{Loss}_{\text{Syst w DG}} = \sum_{i=1}^{N-1}\left(I_i^{DG}\right)^2 r l_i + \sum_{i=1}^{N-1}\left(P_{C_i} + P_{LV_i}\right) \tag{4.25}$$

$$= \sum_{i=1}^{N-1}\left(V_{i_a} - V_{i_b}\right)^2 Y_i^2 r l_i + \sum_{i=1}^{N-1} K'_{Loss}\, I_G + \sum_{i=1}^{N-1}\left(P_{C_i} + P_{LV_i}\right)$$

The above equation is simplified as

$$\text{Loss}_{\text{Syst w DG}} = \sum_{i=1}^{N-1}(I_i)^2 r l_i + \sum_{i=1}^{N-1} K'_{Loss}\ I_G + \sum_{i=1}^{N-1}\left(P_{C_i} + P_{LV_i}\right) \quad (4.26)$$

The equation can be rewritten as

$$\text{Loss}_{\text{Syst w DG}} = \sum_{i=1}^{N-1}(I_i)^2 r l_i + K^T_{Loss}\, I_G + \sum_{i=1}^{N-1}\left(P_{C_i} + P_{LV_i}\right) \quad (4.27)$$

Where $K^T_{Loss} = \sum_{i=1}^{N-1} K'_{Loss}$ (4.28)

Therefore

$$\text{Loss}_{\text{Syst w DG}} = \text{Loss}_{\text{Syst w/o DG}} + K^T_{Loss}\, I_G \quad (4.29)$$

4.1.1 System Loss Reduction Index (SLRI)

A factor which quantifies the loss reduction with the insertion of DG is defined as

$$\text{System Loss Reduction Index (SLRI)} = \frac{\text{Loss in the system with DG}}{\text{Loss in the system without DG}} \quad (4.30)$$

Using the equations (4.8) and (4.29)

$$\text{SLRI} = \ = \frac{\text{Loss}_{\text{Syst w/o DG}} + K_{\text{loss}}\, I_G}{\text{Loss}_{\text{Syst w/o DG}}} \quad (4.31)$$

Where K_{loss} is described by equations (4.9) and (4.28) for the two cases considered.

If SLRI < 1 , the DG has reduced the losses and is beneficial

= 1, the DG has not made any changes in the system

> 1, the DG has introduced more losses in the system.

The Line Loss Reduction Index is defined as [P. Chiradeja, 2005]

$$\mathrm{LLRI} = \frac{\text{Line Loss with DG}}{\text{Line Loss without DG}}$$

$$= \frac{\sum_{i=1}^{K-1}(I_i - I_G)^2\, rl_i + \sum_{i=K}^{N-1} I_i^2\, rl_i}{\sum_{i=1}^{N-1} I_i^2\, rl_i} \qquad (4.32)$$

It is clear from the equation (4.9) that the loss factor K_{loss} must be negative if DG is expected to reduce the losses in the system. Since the loss factor depends on the summation of the difference between the injected DG current and twice the feeder segment current, it attains maximum negative value when it is installed at the remote end N.

The Loss factor and thus, the SLRI are greatly influenced by the power factors of the DG unit. In case, the unit is operating at unity power factor, all the reactive power required by the load is supplied by the source and hence the there may not be any appreciable decrease of line current supplied by the source leading to higher losses and thus, low SLRI.

4.2 Voltage Profile Improvement.

The inclusion of DG in the power distribution network reduces currents in some sections of the feeder thereby reducing the voltage drop caused due to the impedance of the feeder. Eventually this will boost the voltage magnitude at the customer's premises thus improving the voltage profile. The Voltage Profile Improvement Index (VPII) proposed by [Chiradeja, 2005] is defined as

$$VPII = \frac{VP_{w/DG}}{VP_{wo/DG}} \qquad (4.33)$$

Where $VP_{w/DG}$ and $VP_{wo/DG}$ are the voltage profiles of the system with the inclusion of DG and without DG respectively. The Voltage profile is given by

$$VP = \sum_{i=1}^{N} V_i L_i K_i \tag{4.34}$$

With $\sum_{i=1}^{N} K_i = 1$

Where V_i is the pu voltage magnitude at bus i , L_i is the pu load at bus i, K_i is the weighting factor for the load at bus i and N is the total number of buses. The voltage profile recognizes the importance of the load and differentiates the loads with criticality of the loads. However, this approach is quite difficult to adopt in the practical situation since in countries like India, there is no such system of distinguishing between the critical and non critical loads. A very important load may have a separate transformer and thus is not supplied by the usual distribution transformer. In view of this, a simple index to quantify the voltage profile improvement is proposed here.

The voltage at a specific terminal is measured with and without DG in the system. The voltage regulation at any node is defined as

$$VR = \frac{\text{Sending End Voltage} - \text{The voltage at the node on load}}{\text{Sending end voltage}} \tag{4.35}$$

In the present investigation, the sending end voltage is regarded as constant at

11 kV and therefore

$$VR = \frac{11000 - \text{Voltage at the node}}{11000} \tag{4.36}$$

4.2.1 Voltage Regulation Ratio (VRR)

At a specific node, the voltage regulation described by equation (4.36) is calculated first without DG and then with DG by running load flow studies. To quantify the advantage of DG with respect to the improvement of voltage profile, a ratio, Voltage Regulation Ratio, (VRR) is proposed which is described as

$$\text{VRR} = \frac{\text{VR with DG}}{\text{VR without DG}} \tag{4.37}$$

Since the inclusion of DG is expected to improve the voltage at the node considered, the VRI should be less than 1 at all nodes. The expected variation of VRR is shown in fig. 4.

If, VRR < 0, DG has increased voltage at the nodes beyond the base value and is not beneficial

$0 < VRR < 1$, DG has improved the voltage profile and is beneficial.

VRR > 1, DG has decreased the voltages at the nodes and is not beneficial.

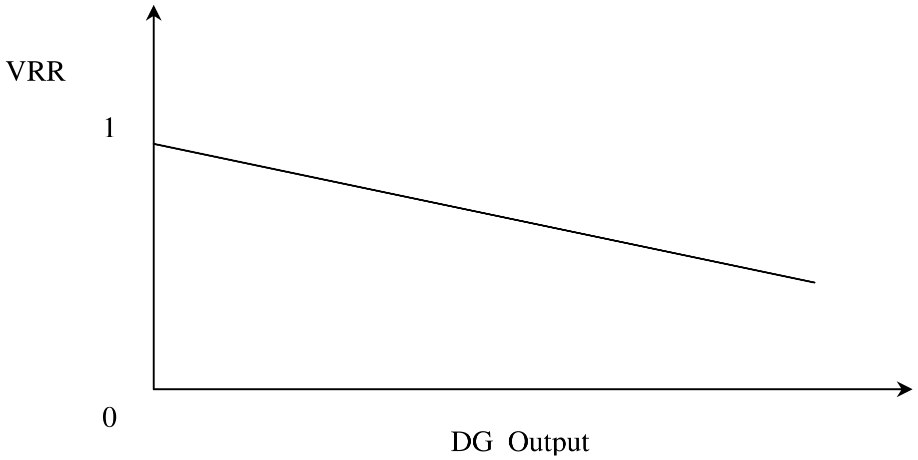


Fig. 4.2 Typical Variation of VRR

In the absence of the DG, VRR is 1 and as the DG is introduced and the output is increased, the Voltage Regulation with DG decreases since the voltage at all the nodes increase. Higher the node voltage, lower the VR and hence lower the VRR. The slope of the curve shown above therefore implies the effectiveness of the penetration of DG. However the penetration of DG should be limited so as not cause a negative value of VRR. From the fig 4.2, it is clear that at some DG output, the curve may cross X axis and may assume negative value afterwards. Which means the voltage at the node is more than the base value.

Following assumptions are made while evaluating VRR in the present investigations.

- The load currents remain constant.
- All the loads are drawing power at 0.8 power factor lagging.
- The DG2 is capable of delivering power at both leading and lagging power factor.

CHAPTER 5

OTHER IMPACTS OF DISTRIBUTED GENERATION

The impact of DG on the estimation of the fault location is studied and estimates are obtained for a single line to ground fault, using the impedance method.

5.1. Estimation of Fault Location

The occurrence of faults cannot be avoided even within a carefully designed and maintained distribution system since they depend on various factors which cannot be controlled. Faults can be classified as Single Line to Ground, Double Line to Ground, Line to Line and Three phase short circuit faults. The accurate and detection of the exact location of the fault is necessary for the reliable operation of the power distribution system. The specific fault location is of great significance in order to provide continuous power supply. The early detection of the fault and an estimation of the exact location of the fault, minimize the long interruptions, causing economical losses to many sensitive and industrial loads. Several methods of Fault Location have been developed in the past [K Shrinivas, et al.(1989) ,A.A. Girgis, et al. (1993), R Das, et al. (2000)]. The fault location estimation methods can be divided into two main groups: those methods based on impedance measurements and those based on travelling waves generated by the short circuit faults. The impedance based methods require measurement of voltages and currents at one point, usually the substation, before and after the fault. Because of the characteristics of the lines and their simplicity, these methods are usually employed. The travelling wave methods are based on the measurements of high frequency components of the travelling waves which are generated by the short circuit faults. Though these methods give precise results, the process is quite complex. These methods are more useful in transmission systems where the power transmitted is usually very large and the quick clearance of the fault is very essential. In a distribution system with less power transaction, impedance methods can be used which give quite satisfactory and reliable results. In this investigation, the method of impedance as described in [Ratan Das, 1998] is used. According to this method, in the event of a fault, apparent impedance is calculated using the measured RMS values of voltage and currents at the substation. The line is assumed to be divided in to a number of sections and using the pre fault data and fault data, the impedance of every section of the line is calculated and modified. The modified reactance is compared with the apparent reactance and an initial estimation of the fault location is made. The exact location is then estimated by evaluating the sequence components of the voltages and currents at the fault.

When a fault occurs, the voltages and currents at the substation will be usually more than those during the normal operation. When a DG unit is introduced in the system, these quantities in the presence of DG will be usually less than those in the absence of DG. If such quantities are used to fix the location of the fault, there may be errors in such estimated fault locations. A typical variation of voltage and currents with respect to the different values of DG and the fault impedance for the single phase to ground fault are shown in fig 5.1 & 5.2. These results are obtained on a practical distribution system shown in fig, 6.1.

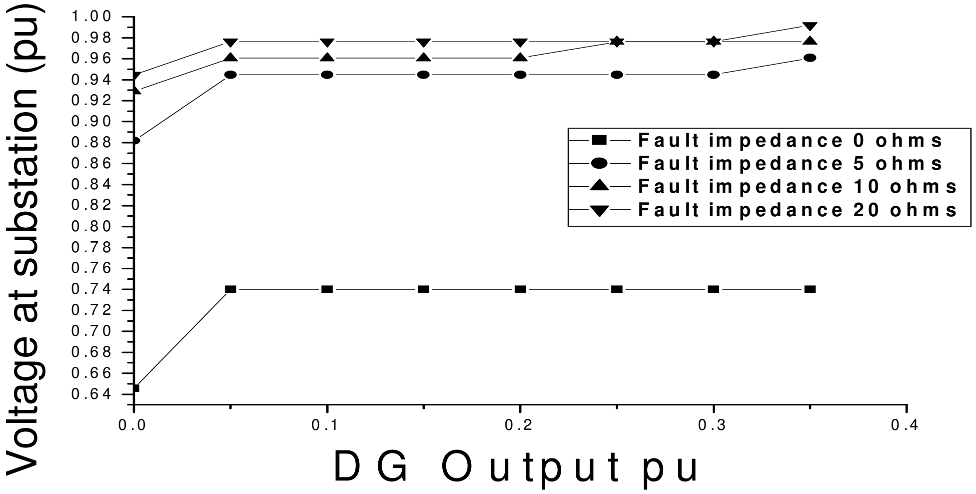


Fig 5.1. Variation of voltage at substation with varying DG output and fault impedance.

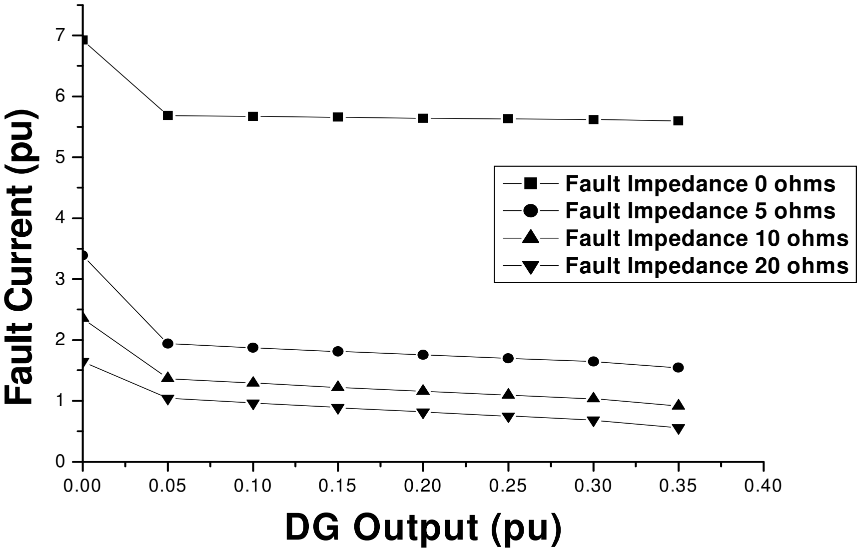


Fig. 5.2. Variation of line current at substation with varying DG output and fault impedance.

In the present work, the estimation of a Single Line to Ground fault location is obtained using the measured values of voltage and currents at the substation with DG embedded in to the system. DG ratings and fault locations are varied in order to study the effect of the DG on the fault location.

When the fault occurs, the line currents change appreciably. If one or more line currents are more than a critical value, then it can conclude that a fault has occurred. By measuring these line currents at the substation, the type of the fault is identified using the flow chart shown in fig. 5.3. The pre fault voltages and currents are saved and are used to model the loads.

5.1.1 FAULT LOCATION USING IMPEDANCE METHOD

The method developed by Ratan Das can be described by considering a single phase to ground fault located between the nodes x and y on a radial system, shown in fig. 5.4. The system consists of a source G and the section between nodes M and N comprise several loads tapped at various points. The fault is situated at F in the section between nodes x and y (= x+1). It is assumed that the fault impedance is completely resistive. The fault location technique consists of the following six steps

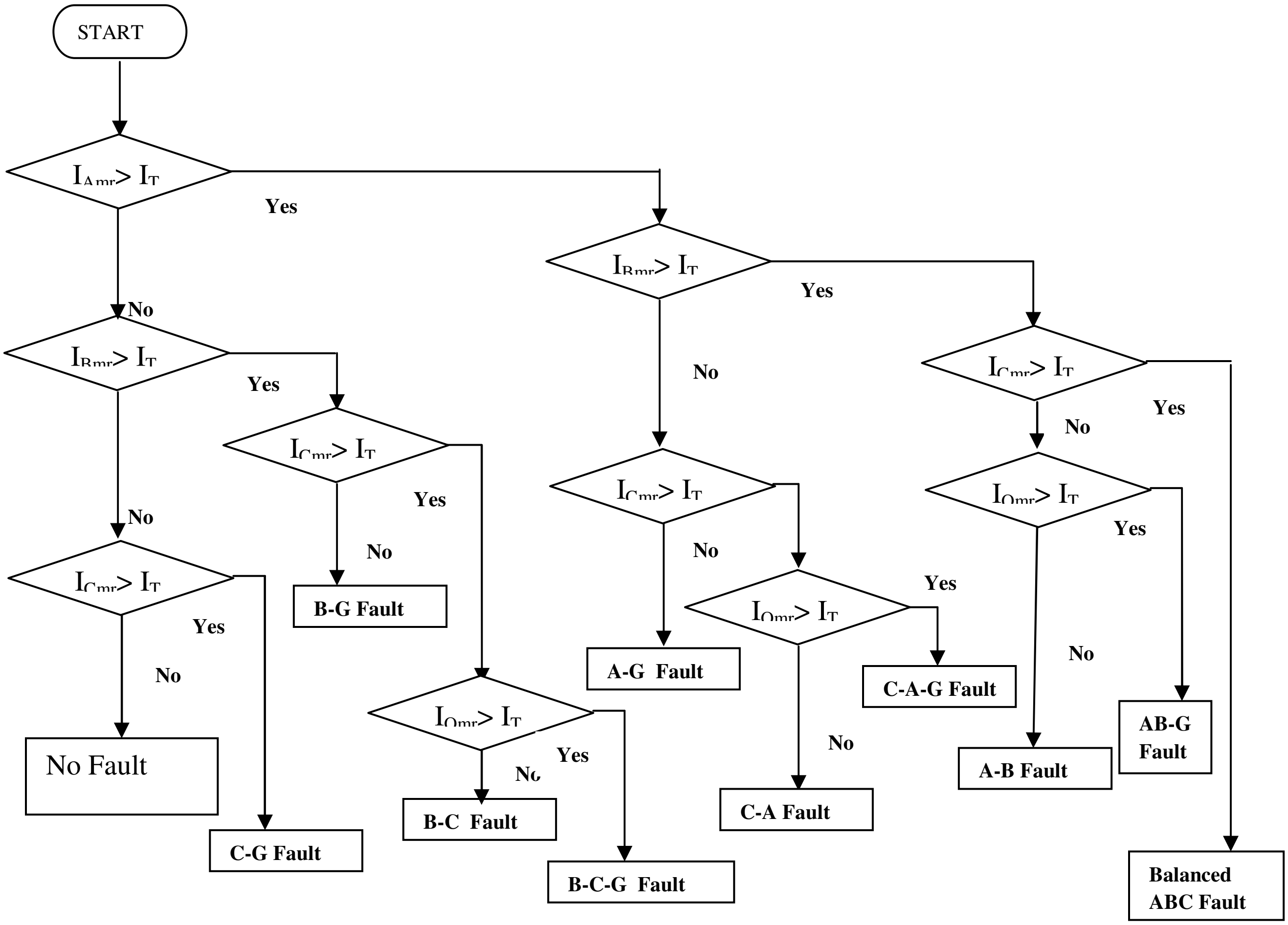


Fig 5.3. Flow chart to detect the occurrence and type of the fault

.

i. Location of Apparent Faulted section.

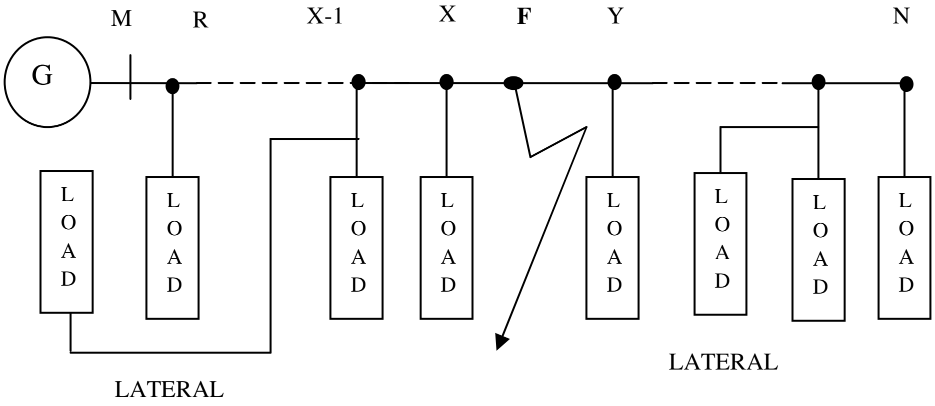


Fig. 5.4 . Single line diagram of a system experiencing a fault

By measuring the phasors of the sequence voltages and currents at the substation, the apparent impedance is calculated first at the line terminal and with the knowledge of the line parameters; modified impedance is calculated for every section of the line which is compared with this basic impedance. A preliminary location of the fault is obtained when the modified reactance becomes more than the apparent impedance. For single phase to ground fault, the apparent impedance is obtained as

$$Z_{app} = \frac{V_{am}}{I_{am}} \tag{5.1}$$

Where V_{am} is the phase voltage of the faulty phase at node m

I_{am} is the current flowing through the faulty line from m to the network

Consider a section between M and the faulty node with terminal nodes as 'a' and 'b'. The modified reactance of this section is calculated as

$$X_{ab}^{m} = X_{1ab} + \frac{X_{0ab} - X_{1ab}}{3} \tag{5.2}$$

Where X_{0ab} and X_{1ab} are the zero and positive sequence reactance of the section of the line between nodes ' a' and 'b' respectively. The value of the reactance of the previous section is added to this value and a modified reactance is obtained. This modified reactance is compared with the apparent impedance and if it is found to be greater than the apparent impedance, then the fault lies in the section between the nodes ‘a’ and ‘b’. Else, the fault is located beyond ‘b’. The procedure is repeated and the impedance of each section is modified until the section in which the fault has occurred, is located. Once the Faulty section is identified, the following five steps are used to locate the exact location.

ii. Modified Radial System

On detecting a fault, the system has to be modeled suitably. The modeling of a distribution system is very complex since it consists of many laterals also. In order to simplify the calculations, the loads on all the laterals between the substation and the faulty section neglected as shown in Fig. 5.5.

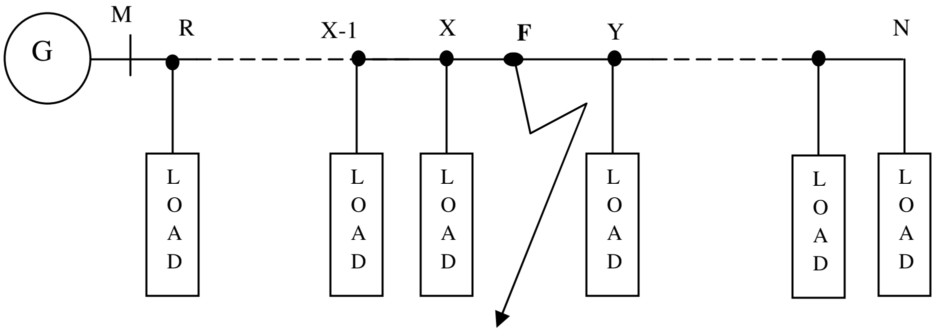


Fig 5.5. Single line diagram of the modified radial system

iii. Load Modeling

The loads are modeled by evaluating the load constants such as admittance and suseptance. A load connected at node ‘r’, is described by

$$Y_r = \left\{ G_r |V_r|^{n_p^{-2}} + jB_r |V_r|^{n_q^{-2}} \right\} \tag{5.3}$$

Where V_r represents the voltage at node r;

Y_r is the load admittance,

G_r and B_r are constants proportional to the conductance and susceptance respectively and the values of the pre fault voltages and currents are used to determine these values.

n_p and n_q are the response constants for the active and reactive components of the load and for three types of loads are:-

$n_p = n_q = 0$, for constant power load.

$n_p = n_q = 1$, for constant current load.

$n_p = n_q = 2$, for constant impedance load.

Different methods for obtaining the values of n_p and n_q are available in the literature. In the present investigation these values are assumed.

iv. Voltages and currents at Fault and at remote end.

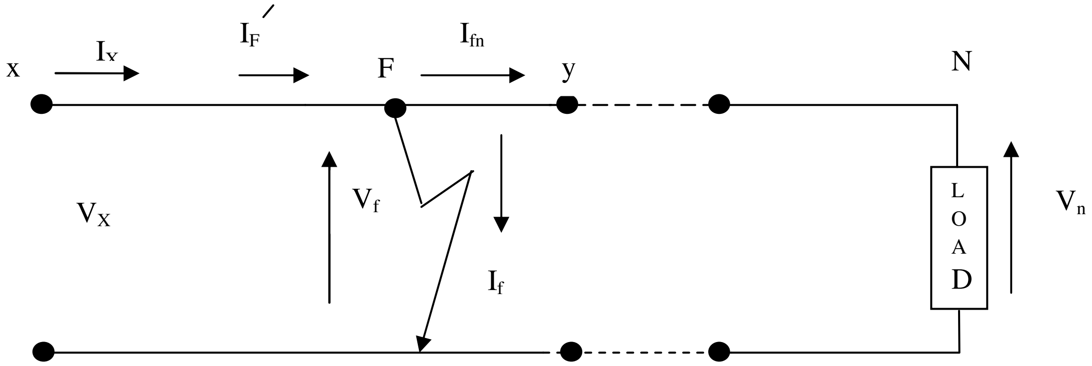


Fig.5.6. The voltages and currents at nodes F and N during the fault.

The simplified single line diagram from node x to the remote node N is shown in fig 5.6, in which all the loads up to node F are neglected and all the loads beyond F are shown to be connected at the remote end as a consolidated load. Considering the segment of the line between the nodes x and F

The voltages and currents at nodes F and x are related by

$$\begin{bmatrix} V_F \\ I_{f'} \end{bmatrix} = \begin{bmatrix} 1 & -sBxy \\ -sCxy & 1 \end{bmatrix} \begin{bmatrix} V_x \\ I_x \end{bmatrix} \tag{5.4}$$

In the above equation, the distance between node ‘x’ and the fault point ‘F’, is represented as ‘s’ in per unit value.

B_{xy} and C_{xy} are the impedance and the shunt admittance of the section of the line between x and y respectively and the constants A and D are assumed to be equal to 1.

The sequence components of voltages and currents at F during the fault are evaluated by replacing all the loads beyond F, into a consolidated load connected at the remote node N.

The sequence voltages and currents at nodes N and F during the fault are related by the following equation

$$\begin{bmatrix} V_n \\ I_{n'} \end{bmatrix} = \begin{bmatrix} D_e & -B_e \\ -C_e & A_e \end{bmatrix} \begin{bmatrix} 1 & -(1-s)B_{xy} \\ -(1-s)C_{xy} & 1 \end{bmatrix} \begin{bmatrix} V_f \\ I_{fn} \end{bmatrix} \tag{5.5}$$

Where A_e, B_e, C_e and D_e are the equivalent constants of the cascaded section between nodes y and N.

The currents at node F are related by

$$I_{Fn} = I_{F'} - I_F \tag{5.6}$$

Rearranging equations 5.4, 5.5 and 5.6, and neglecting second and higher order terms in s, the following equation is obtained.

$$\begin{bmatrix} V_n \\ I_f \end{bmatrix} = \frac{1}{K_v + sK_w} \begin{bmatrix} K_m + sK_n & sK_p \\ K_q + sK_r & K_v + sK_u \end{bmatrix} \begin{bmatrix} V_x \\ I_x \end{bmatrix} \tag{5.7}$$

Where K_m, K_n, K_p, K_q, K_r, K_u, K_v and K_w are complex parameters and are computed using the line parameters. (Details of calculations are shown in annexure 1).

v. Estimating the location of the Fault

The fault impedance is assumed to be resistive. Therefore, The value of'S', is evaluated by equating the ratio of voltage and current at the fault to the resistance. For a single line to ground fault on phase A,

$$\frac{V_f}{I_f} = \frac{V_{of} + V_{1f} + V_{2f}}{I_{of} + I_{1f} + I_{2f}} = R_f \qquad (5.8)$$

Where V_{of}, V_{1f}, V_{2f} and I_{0f}, I_{1f} and I_{2f} are zero, positive and negative sequence voltages and current phasors at the fault F and R_f is the fault resistance..

The LHS of equation 5.8 is complex and is equated to a real term. Hence the imaginary term of the above equation must be zero. After substituting the value of sequence components of voltages and currents the following equation is obtained

$$\operatorname{Im}\left(\frac{K_A + sK_B}{K_C + sK_D}\right) = 0 \qquad (5.9)$$

Where K_A, K_B, K_C and K_D are complex parameters, which are expressed into real and imaginary parts as

$K_A = K_{AR} + jK_{AI}$,

$K_B = K_{BR} + jK_{BI}$

$K_C = K_{CR} + jK_{CI}$

$K_A = K_{DR} + jK_{DI}$

Substituting the values of the constants and simplifying, the value of 's' is obtained as

$$s = \frac{K_{AR} + K_{CI} - K_{AI} K_{CR}}{\left(K_{CR} K_{BI} - K_{CI} K_{BR}\right) + \left(K_{DR} K_{AI} - K_{DI} K_{AR}\right)} \tag{5.10}$$

vi. Converting multiple estimates into a single estimate.

The presence of laterals give rise to multiple estimates of the fault location. These estimates are collected and comparing with the information from the fault indicators provided in the system, single estimate may be arrived at.

5.1.2 Effect of DG in Estimation of Fault Location.

With the high penetration of DG in the distribution system, the fault location becomes quite complex. The impedance method must be modified in order to account for the contributions from the DGs and to avoid large fault location errors. Consider a distribution system with DG shown in fig 5.7

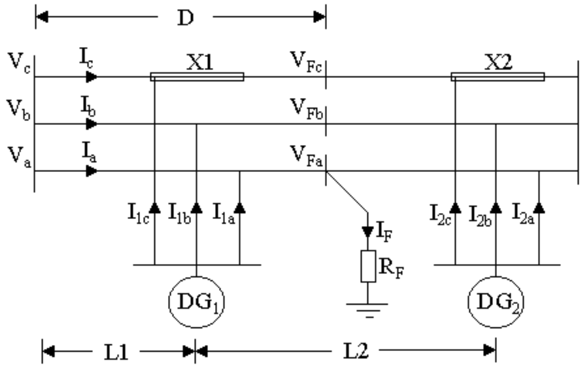


Fig 5.7. Figure showing a distribution system with DG

DG1 and DG2 are situated at a distance L1 and L2 from the sending end respectively. Consider a fault on the section of the feeder between the DG locations, at a distance D from the sending end. With the introduction of DG, the current distribution will now be different than that without DG.

The relationship between the voltages at the sending end and the fault is written as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = [Z_{abc} \times L_1] \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + [Z_{abc} \times (D - L_1)] \begin{bmatrix} I_a + I_{1a} \\ I_b + I_{1b} \\ I_c + I_{1c} \end{bmatrix} + \begin{bmatrix} V_{Fa} \\ V_{Fb} \\ V_{Fc} \end{bmatrix} \tag{5.11}$$

where:

$[Z_{abc}]$ = 3x3 impedance matrix in terms of impedance per unit length.

I_{1a}, I_{1b}, I_{1c} = currents from DG1

The initial contributions to the fault current from the DGs and the exact location of the fault are not known, the DG currents are neglected and an initial estimation of the fault location is obtained using the impedance method mentioned earlier. Then an iterative process is used to determine the accurate distance to the fault. The steps in this process are described below.

(1) Using this estimated fault distance, the voltages at the fault are calculated by rearranging and solving equation 5.12. Initially the DG currents, I_{1a}, I_{1b}, and I_{1c}, are assumed to be zero.

$$\begin{bmatrix} V_{Fa} \\ V_{Fb} \\ V_{Fc} \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - [Z_{abc} \times L_1] \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} - [Z_{abc} \times (D - L_1)] \begin{bmatrix} I_a + I_{1a} \\ I_b + I_{1b} \\ I_c + I_{1c} \end{bmatrix} \tag{5.12}$$

(2) The fault voltages are then used to solve for the DG currents on phase A by relating the voltages at the fault to the voltages at the points where the DG's are connected.

To calculate the current contributions from DG1:

First the sum of the sending-end current and the current from DG1 is calculated:

$$\begin{bmatrix} I_a + I_{1a} \\ I_b + I_{1b} \\ I_c + I_{1c} \end{bmatrix} = \left[Z_{abc} \times (D - L_1)\right]^{-1} \begin{bmatrix} V_{1a} - V_{Fa} \\ V_{1b} - V_{Fb} \\ V_{1c} - V_{Fc} \end{bmatrix} \tag{5.13}$$

where: V_{1a}, V_{1b}, V_{1c} = the voltages at DG1.

From equation (12) the current contributing from DG1 is found by subtracting the currents from the sending-end from the total current feeding the fault from the left side:

$$I_{1a} = (I_a + I_{1a}) - I_a \tag{5.14}$$

To calculate the current contributions from DG2:

$$\begin{bmatrix} I_{2a} \\ I_{2b} \\ I_{2c} \end{bmatrix} = -\left[Z_{abc} \times (L_2 - D)\right]^{-1} \begin{bmatrix} V_{2a} - V_{Fa} \\ V_{2b} - V_{Fb} \\ V_{2c} - V_{Fc} \end{bmatrix} \tag{5.15}$$

where: V_{2a}, V_{2b}, V_{2c} = the voltages at DG2.

I_{2a}, I_{2b}, I_{2c} = currents from DG2

(3) Then the fault current is updated by adding the sending-end current to the DG currents:

$$I_F = I_a + I_{1a} + I_{2a} \tag{5.16}$$

(4) The updated fault current and the fault voltages are then used to solve for the distance to the fault, using the equation :

$$Im\,\frac{V_f}{I_f} = 0 \tag{5.17}$$

Once the new distance is calculated, next iteration begins by going back up to step 1. The iterative process is then continuously repeated until the difference between the present distance calculated and the previously calculated distance is very small.

This fault algorithm shows the basic steps in which to calculate an accurate fault distance when a single line-to-ground fault is located between DG1 and DG2 given a system as seen in Figure 5.7. For other types of systems and faults, some of the data needed for the equations will vary but the process will remain the same.

5.2 kVA delivered by the source

The main advantage of DG is that it decreases the burden on the source. When the load demand is more, part of the power is supplied by the DG and the remaining is to be supplied by the source. It can be therefore concluded that with a DG unit capable of injecting large power to the distribution network, the source then will have to supply a meager amount of power.

Though this statement is true for active power, the same is not true with reactive power. The operating power factor of the DG unit has a direct influence on the reactive power supplied by the source. Majority of the loads on the power distribution network are inductive in nature and demand reactive power for their operation. If the DG unit is operating at unity power factor (as in case of solar PV generation), the required reactive power has to be supplied by the source and the total kVA therefore increases. It is therefore essential to study this issue before fixing up the operating power factor of the DG source.

5.3 Faults on LV side of the Distribution System.

When a fault occurs on the HV side, the substation currents change significantly and the fault can be detected by measuring these values. If a fault occurs on the LV side, the changes in the substation voltages and currents are very small and these may be misunderstood for the changes due to the load variations. If the protection circuit does not operate on the LV side, this situation continues and a large power continues to flow through the faulty line. The situation becomes still worse with the presence of DG in the system. This has to be properly taken care while installing the DG.

CHAPTER 6

RESULTS

This chapter discusses the results obtained by analyzing a practical distribution system operating both with and without distributed generation units. The benefit indices discussed in chapter IV are evaluated for varying locations and ratings of DG. The mathematical models for the solar pv generation and the power generated using MSW, developed in chapter III, are used to estimate the power available and are incorporated as DG units in the power distribution system. The simulation tests are focused mainly on the analysis of the impact of DG on (1) Line loss reduction, (2) Voltage profile improvement and (3) the estimation of fault location. The simulation tests are carried for various cases and the results are presented.

6.1 Description of the system under study.

A practical 36 bus, distribution feeder namely the 11 KV, UAS feeder in Dharwad, shown in fig 6.1, is considered. The system consists of 35 distribution transformers with various ratings. The details of the distribution transformers are given in table 6.1. The base MVA used in the study is 2.0 MVA. The conductor used is Rabbit with resistance of 0.0097 pu/km and reactance of 0. 0060143 pu/km. The lengths of the feeder segments are given in table 6.2. The total connected load on the system is 2300 KVA and the peak demand for the year 2011-12 is 2000 KVA at a pf of 0.8 lag. The connected loads on the transformers are listed in table 6.3

The system consists of two DG units described below.

1. Solar PV generation (DG1), of rating 270 KWp connected at node No 28
2. MSW derived power generation with a conventional generator (DG2), of rating 800 KW connected at node No 43.

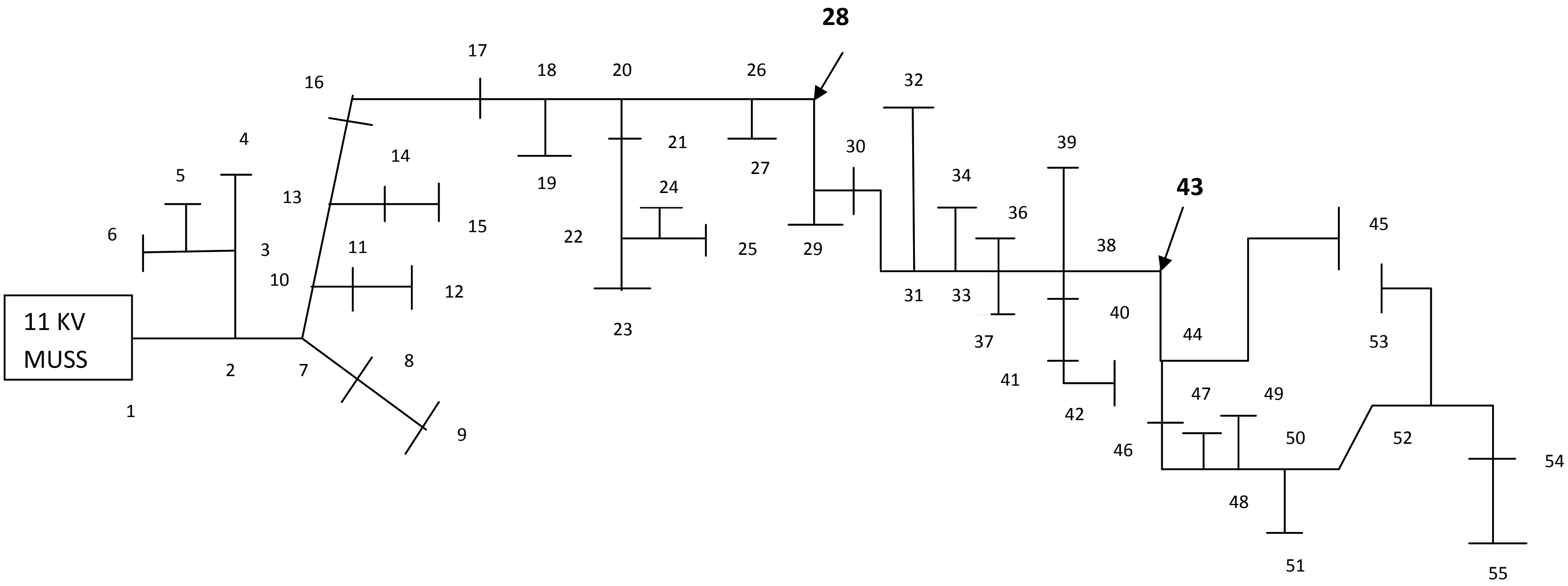


Fig 6.1. The 11 KV UAS Feeder with the proposed positions of both the DG units

Table 6.1. Details of transformers in the system

Rating (KVA)	63	100	250
Number	16	18	1
No Load Losses (Watts)	180	260	470
% Impedance	4.5	4.5	4.5

Table 6.2. Distribution System Line Data

From node	To node	Length(mtrs) (mtrs)	From node	To node	Length(mtrs) (mtrs)	From node	To node	Length(mtrs) (mtrs)
1	2	300	18	20	80	35	38	90
2	3	80	20	21	60	38	39	160
3	4	80	21	22	80	38	40	80
3	5	60	22	23	60	40	41	80
5	6	60	22	24	60	38	42	180
2	7	120	24	25	60	42	43	120
7	8	60	20	26	80	43	44	120
8	9	60	26	27	80	43	45	60
7	10	120	26	28	120	45	46	260
10	11	60	28	29	60	46	47	80
11	12	60	29	30	40	46	48	110
10	13	120	30	31	360	48	49	60
13	14	60	31	32	80	48	50	180
14	15	60	31	33	80	50	51	60
13	16	170	33	34	90	50	52	290
16	17	90	33	35	90	52	53	90
17	18	400	35	36	60	52	54	420
18	19	60	35	37	90	54	55	60

Table 6.3. Details of the loads on the transformers.

Transformer No	Load (kVA)	Transformer No	Load (kVA)
1	61	19	61
2	61	20	61
3	38	21	61
4	38	22	38
5	38	23	38
6	38	24	61
7	38	25	61
8	38	26	38
9	38	27	38
10	61	28	61
11	38	29	61
12	61	30	61
13	61	31	61
14	38	32	38
15	61	33	38
16	38	34	61
17	61	35	153
18	61		

6.2 Method of Study

Following steps are followed to evaluate the impacts of DG and also to quantify the benefits of the proposed indices.

- The power outputs of both DG1 and DG2 are estimated.
- The details of the distribution system are collected and the system is simulated using CYMEDIST computer simulation program and the DG units are incorporated in the simulated system.
- Load flow studies are conducted for all the specified cases and the results are obtained.
- The results are analyzed and the impacts of DG are evaluated.

Specific cases considered for study

The impact of DG in respect of Line Loss Improvement and Voltage Profile Improvement is studied using three different cases. For each of these cases, the DG outputs are varied and the impacts are assessed.

The three cases are shown below.

Case No	DG1	DG2
1	ON	OFF
2	OFF	ON
3	ON	ON

For cases 2 and 3, operating power factor of DG2 is varied from 0.8 lag, 0.9 lag, unity, 0.9 lead and 0.8 lead. Fault location estimation is analyzed using case 3.

While carrying out the tests, the following assumptions are made.

- All the loads draw power at 0.8 lagging.
- The loads on the low voltage side are distributed over line of length 300 mtrs.
- The core losses of the transformers remain constant at their rated value.

6.3 Loss Reduction Analysis.

The simulation results are given in figures 6.2 to 6.8. These results reveal that the inclusion of DG reduce the line losses, independent of the load models selected. This is in agreement with equations 4.4 and 4.27. It can be shown from 6.2a and 6.2b that, LLRI decreases remarkably with power output of DG but SLRI decreases marginally, since the core losses of the transformers and the LV side losses remain constant being independent of the presence of DG. For the cases considered, up to 30 % loss reduction [(1-SLRI) X 100] (Case 3 with 0.625 pu of DG) is achieved with the employment of DG (Fig 6.4).

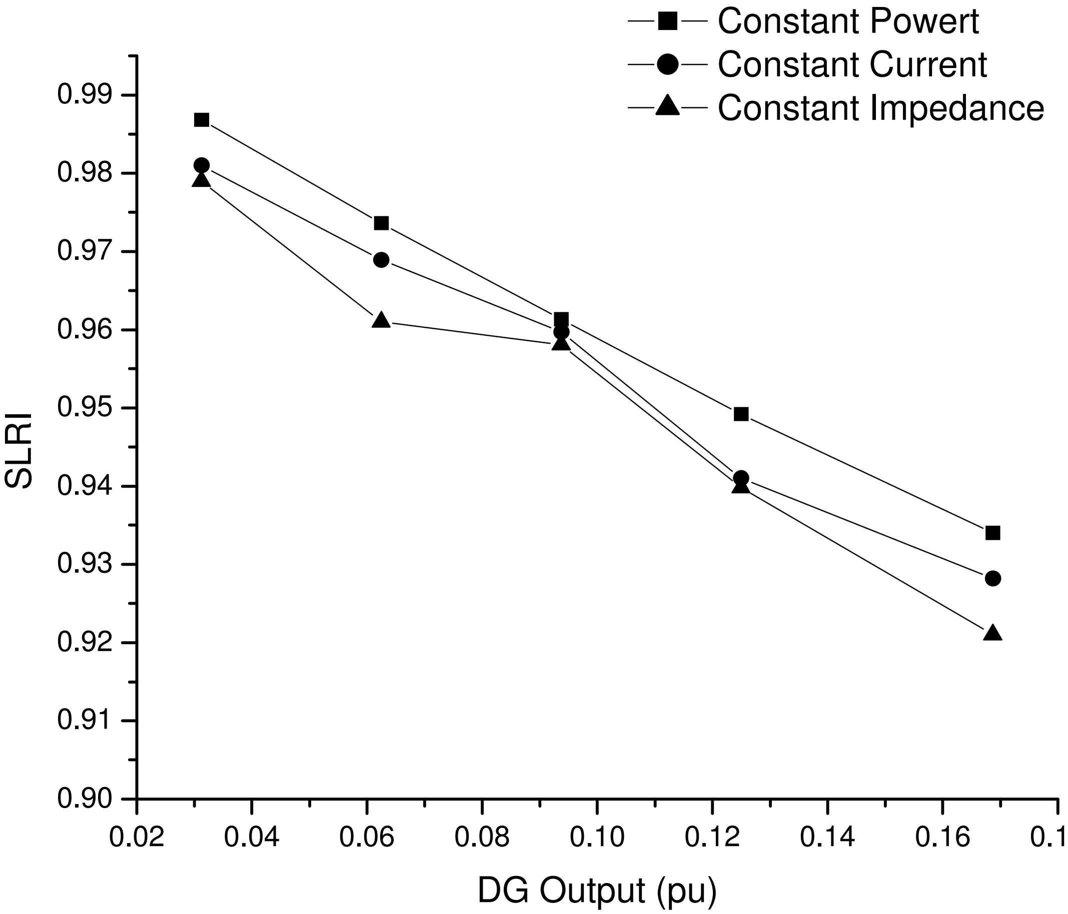


Fig. 6.2 a. Variation of SLRI with DG Output. (Case 1)

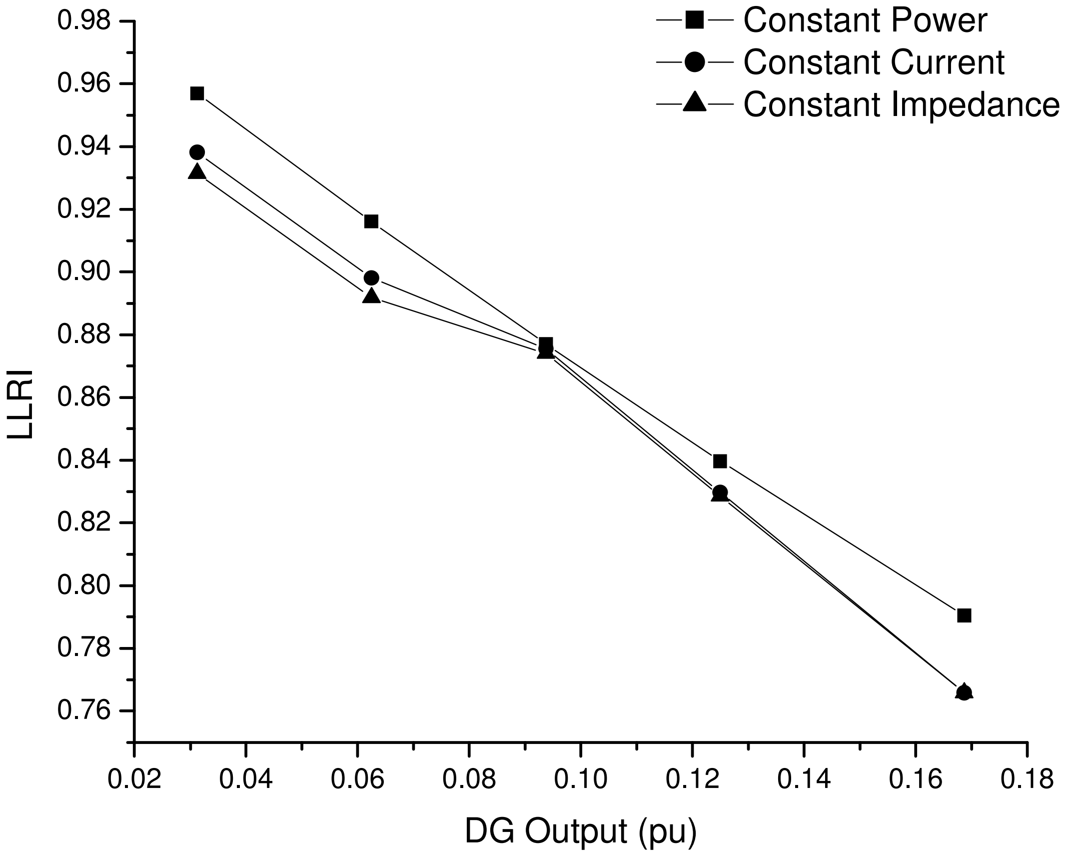


Fig. 6.2 b. Variation of LLRI with DG Output. (Case 1)

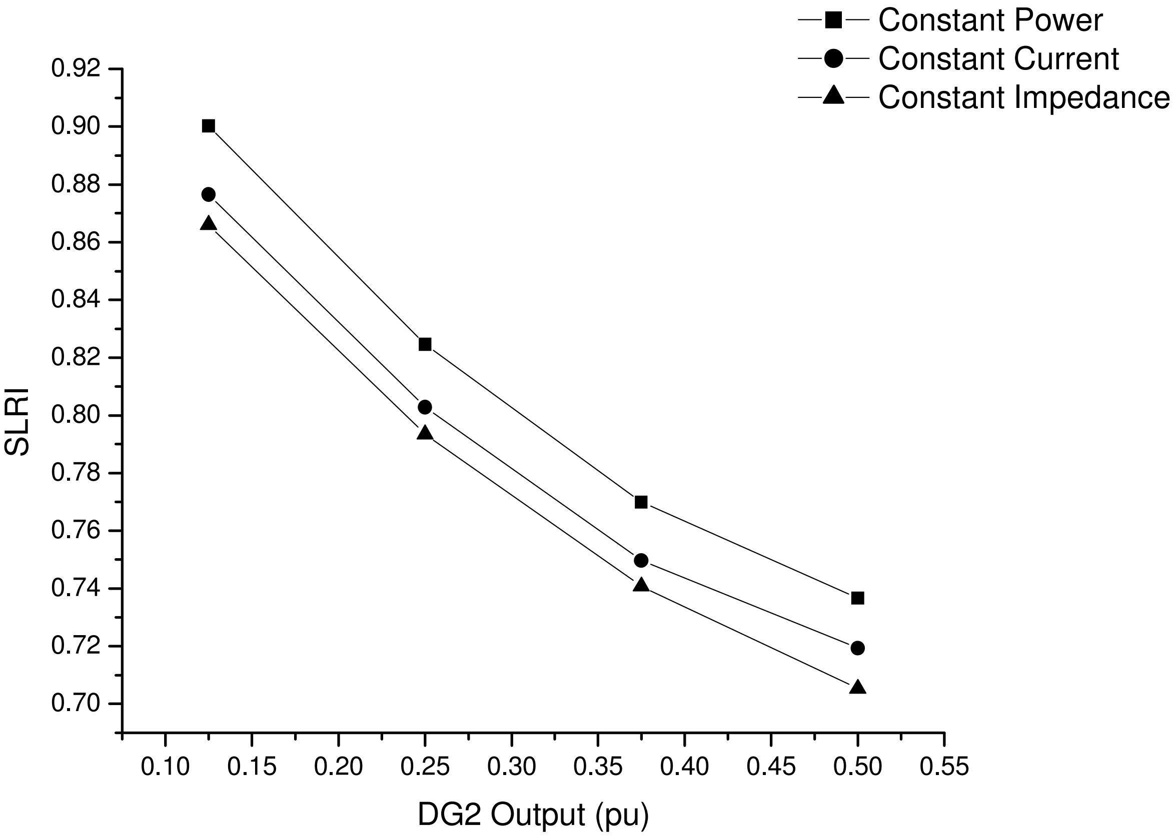


Fig. 6.3. Variation of SLRI with DG Output. (Case 2)

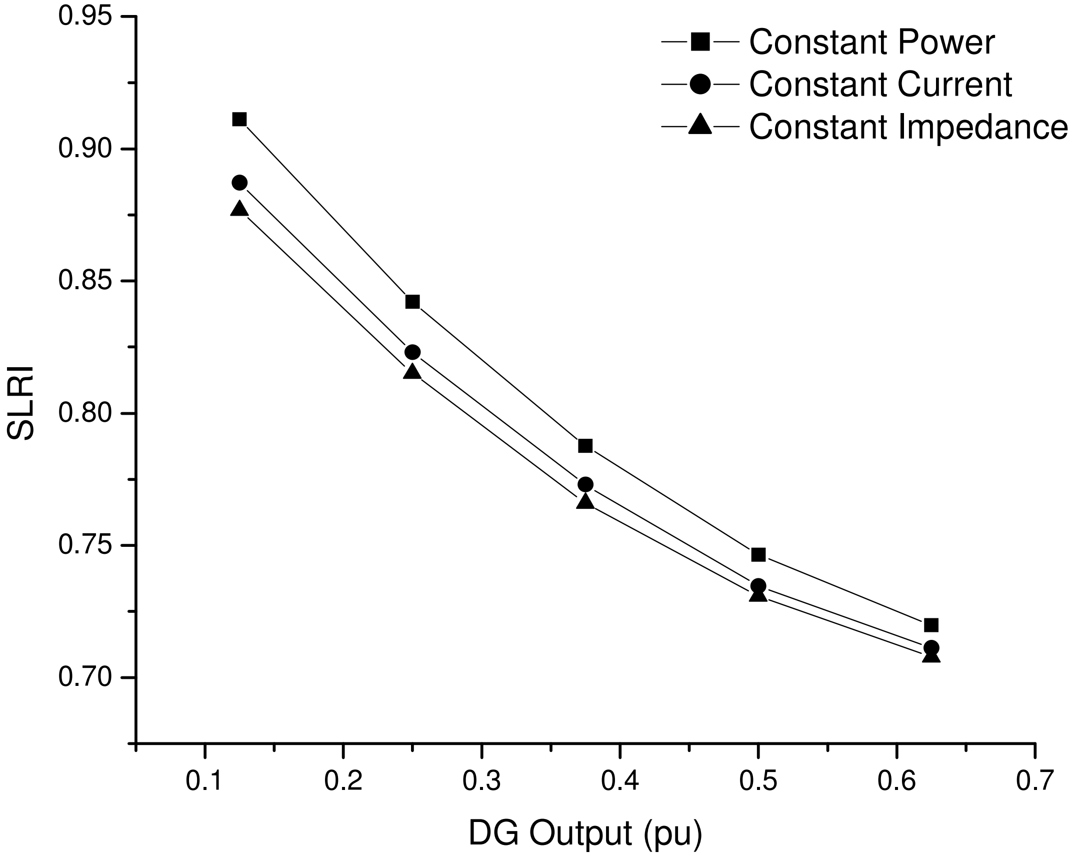


Fig. 6.4. Variation of SLRI with DG Output. (Case 3)

Fig 6.5 shows the variation of the SLRI with high penetration of DG (case 3). The high penetration of the DG can be simulated by reducing the load demand while retaining the DG ratings. For the case considered, a reduced load demand of 600 KW at 0.8 pf lag is considered and output of DG2 is varied. It can be seen that with the increase in the DG output, SLRI decrease but again show an increasing trend after a threshold value. This is because, the system receives more power from DG than required and hence the line loss increase appreciably since the rate of change of loss changes from negative to positive with large values of I_{DG}. This should be considered before fixing up the value of DG output. Under such a case, one DG unit can be switched off so that the advantage of lower SLRI can be enjoyed.

It is also observed that although all the three models have approximately same amount of losses, the constant current model results into higher losses in comparison with other models. However, the trend of SLRI remains same irrespective of the load model selected.

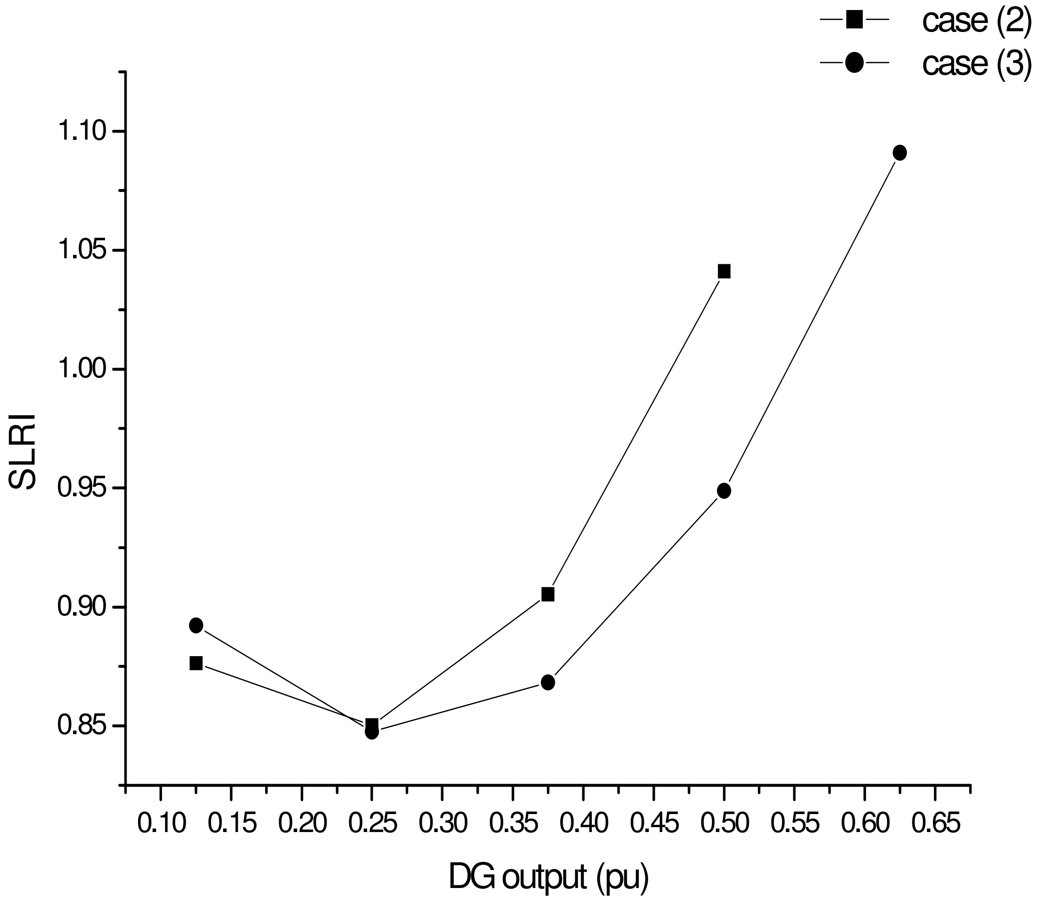


Fig 6.5 SLRI for Load Demand of 600 KW with DG2 operating at 0.8 pf lag

The operating power factor of DG also influences the SLRI. As the DG operating power factor changes from lagging to leading, the DG unit absorbs reactive power from the lines. This increases the current in the lines, resulting in higher electrical line losses. Hence SLRI will have lower values with DG operating at lagging power factor and increase under leading power factor. This can be observed from fig 6.6. This factor should be considered while fixing the operating power factor of DG.

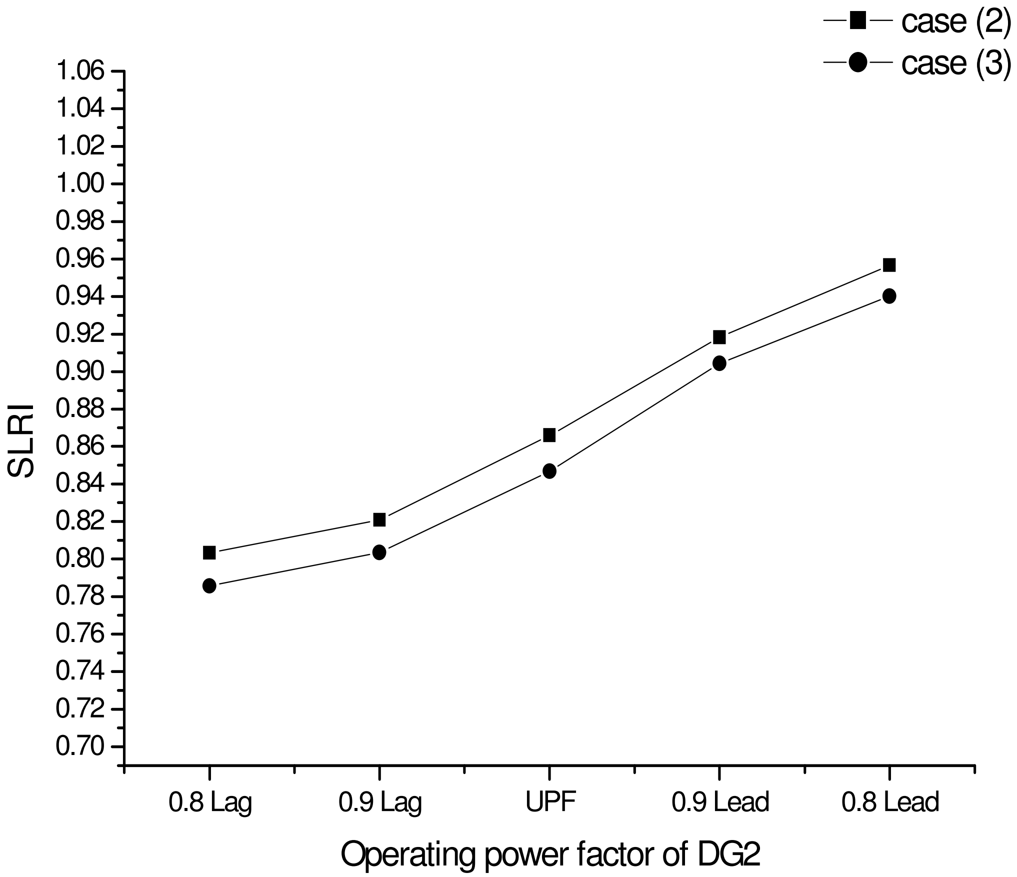


Fig 6.6 Variation of SLRI with operating power factor of DG2

The variation of loss factor is shown in fig. 6.7. It is clear from the figure the Loss Factor remains fairly constant and hence the loss reduction depends mainly on the current injected by the DG unit. When the injected current I_G is more than the branch current I_i, loss factor becomes positive and the total losses in the system increase, leading SLRI to acquire a value greater than one. This is in agreement with the equation (4.9) and (4.28). It is observed that the variation of loss factor remains almost same for all the three models of the load.

The location of DG is also very critical in deciding the loss reduction. It is evident from figure 6.8 that SLRI show a decreasing trend when DG is located away from the substation because, under such circumstances, the DG will be near the load and greater part of the trunk line will be carrying reduced current, causing reduced line losses. This issue should be considered before installing DG in the system.

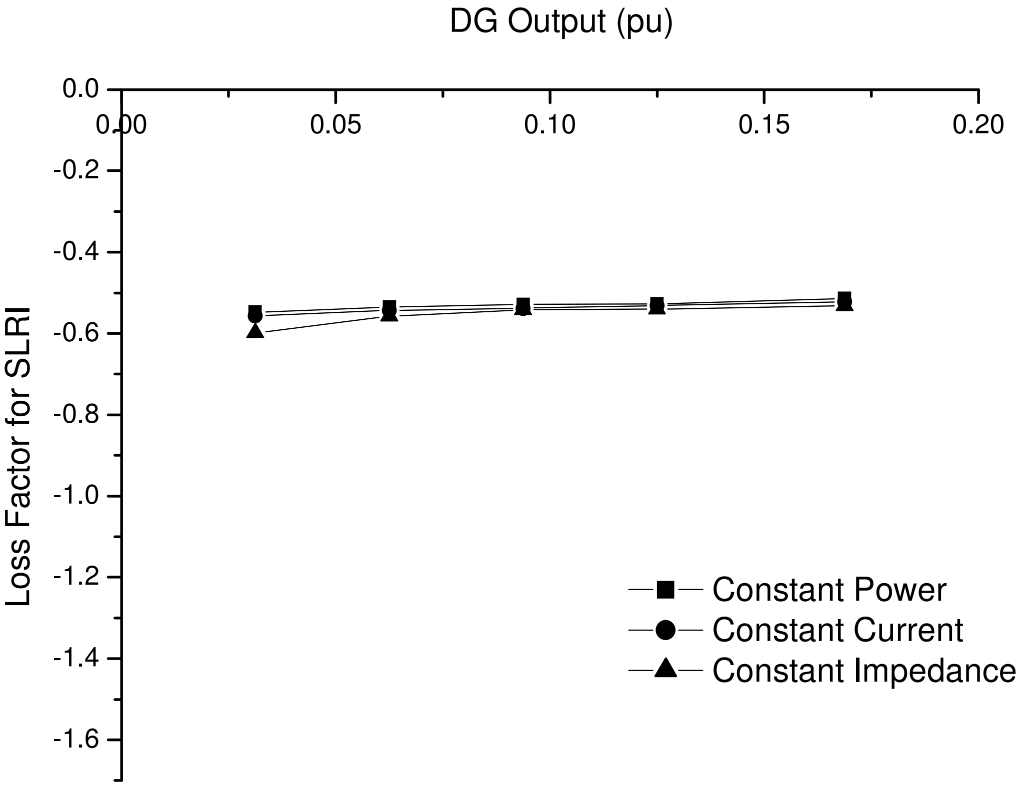


Fig 6.7. Figure showing the variation of Loss Factor with DG output. (case 1)

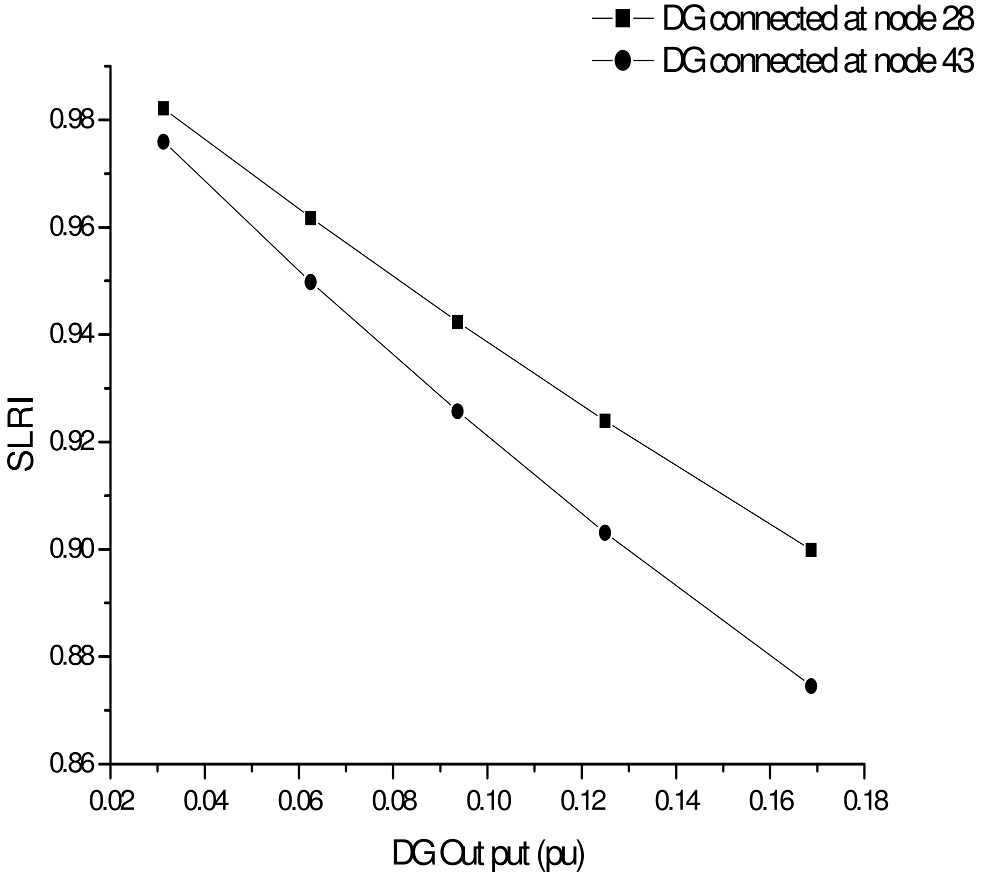


Fig 6.8 Variation of SLRI with the same DG unit connected at two different locations

The effect of the load power factor on SLRI is shown in fig. 6.9 which is obtained with constant current modeling of the loads. To study the impact of this, SLRI is evaluated for the load power factor of 0.8 lag, 0.9 lag, upf, 0.9 lead and 0.8 lead with DG1 operating at unity power factor and DG2 operating at 0.8 pf lag. It is observed from the results that the SLRI show increasing trend as the load power factor changes from lagging to leading. With the loads operating at lagging power factor, total power demand on the substation decreases by an amount equivalent to that of DG. However, when the loads are operating at leading power factor, the total demand on the substation increases since the DG does not supply the leading reactive power required by the load. Hence under such circumstances, the line currents will be higher, resulting into higher line losses and increased SLRI.

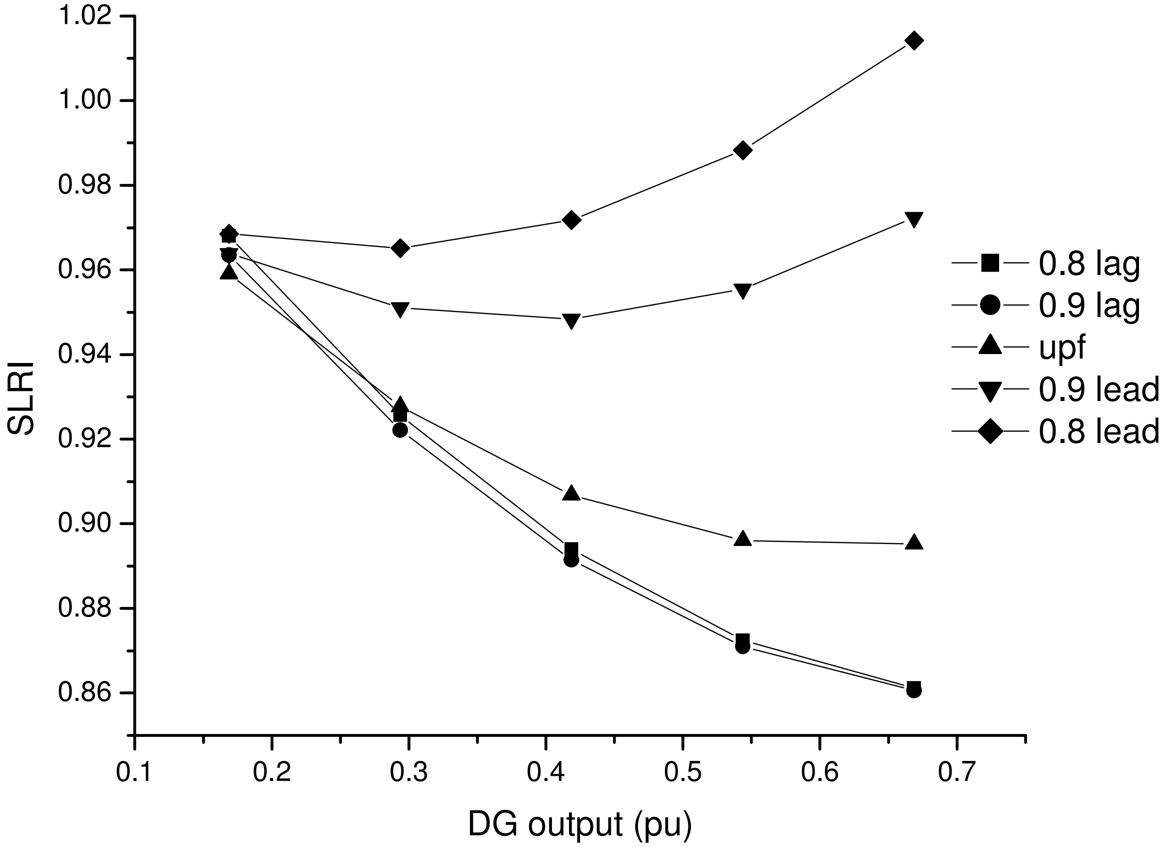


Fig 6.9 Variation of SLRI for varying load power factors.

6.4 Voltage Regulation Ratio. (VRR)

Another major advantage of distributed generation is voltage profile improvement. The voltages at all the nodes are found to increase with DG incorporated in to the system. To illustrate this, two nodes, 20 and 52 are considered in this investigation. One node is nearer to the substation and the other is away from the substation, nearer to the remote end. The variation of VRR, for various cases is shown in figures 6.9 – 6.11. It is seen from the figures that as the output of DG increase, VRR decrease indicating rise in the node voltages. However, higher penetration of DG may result in node voltages becoming more than the base voltage. Fig 6.12 shows that when the DG output crosses approximately 0.38 pu, the voltage at the node 20, is more than the base voltage resulting into negative VRR. This is because, the reverse flow of current in the feeder segments. Node 52 also exhibits the same scenario with larger DG output.

DG operating power factor also influence VRR. As the operating power factor of DG changes from lagging to leading, VRR increases indicating that node voltage has decreased. It can be seen from figure 6.13, that DG is not advantageous with leading power factor. This is because DG draws reactive power from the lines resulting into higher voltage drops in the lines.

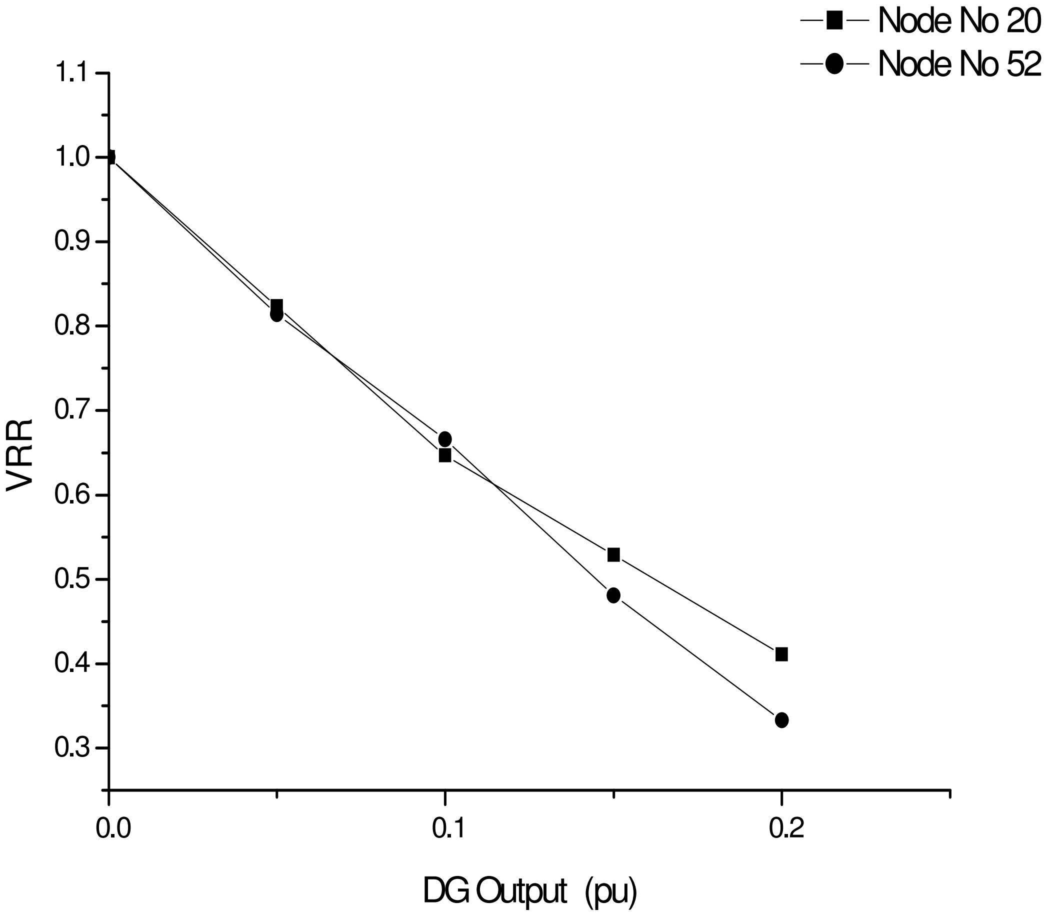


Fig. 6.10 Figure showing the variation of VRR Vs DG Output for Case 2.

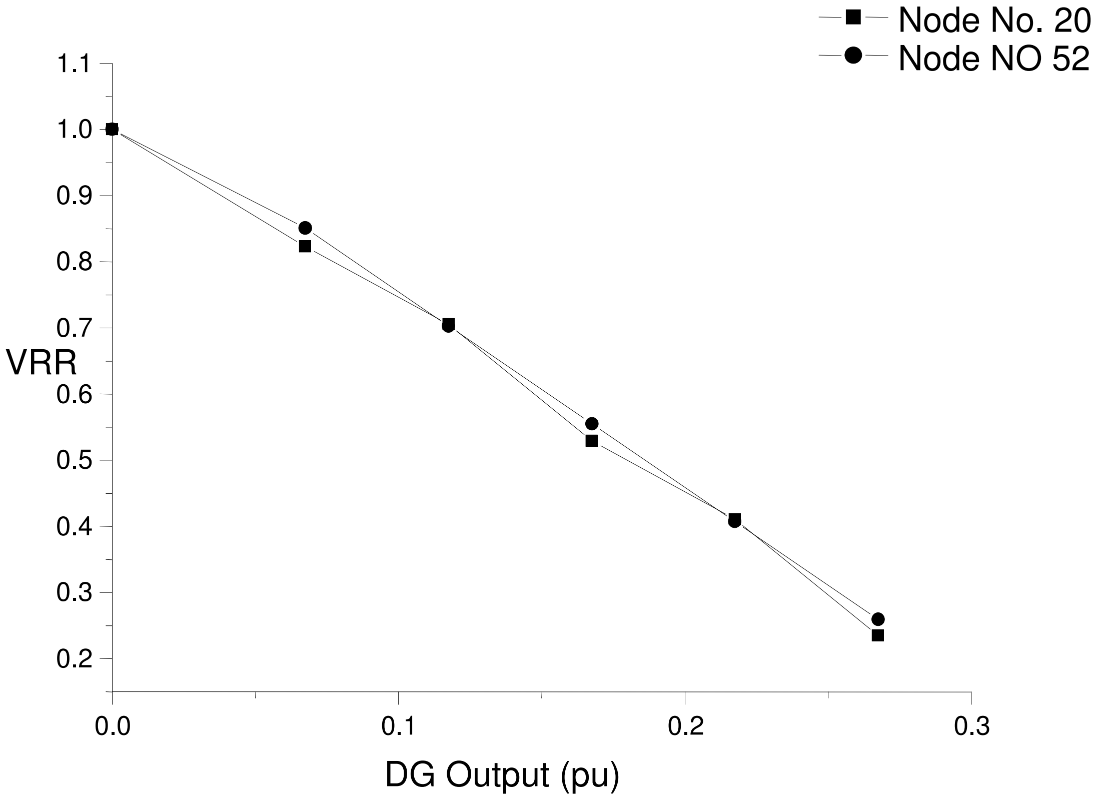


Fig. 6.11 Figure showing the variation of VRR VS DG output (pu) Case 3

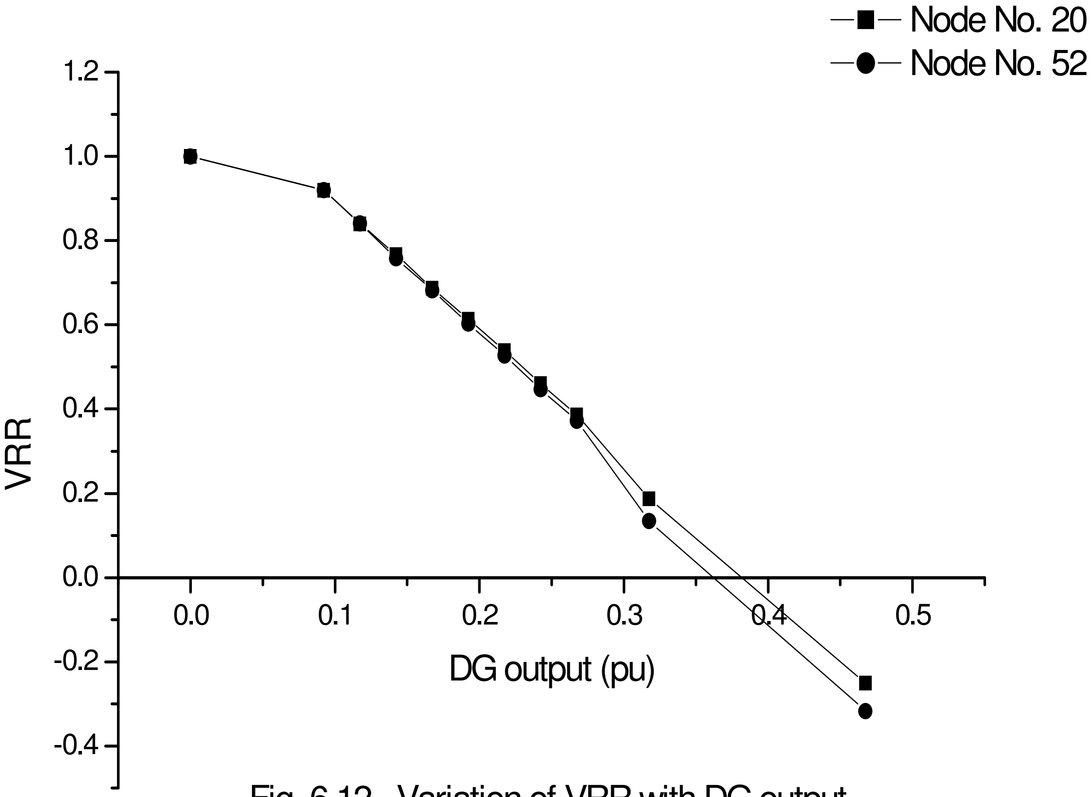


Fig. 6.12 Variation of VRR with DG output.
(DG1 at 270 KW and DG2 with varying output)

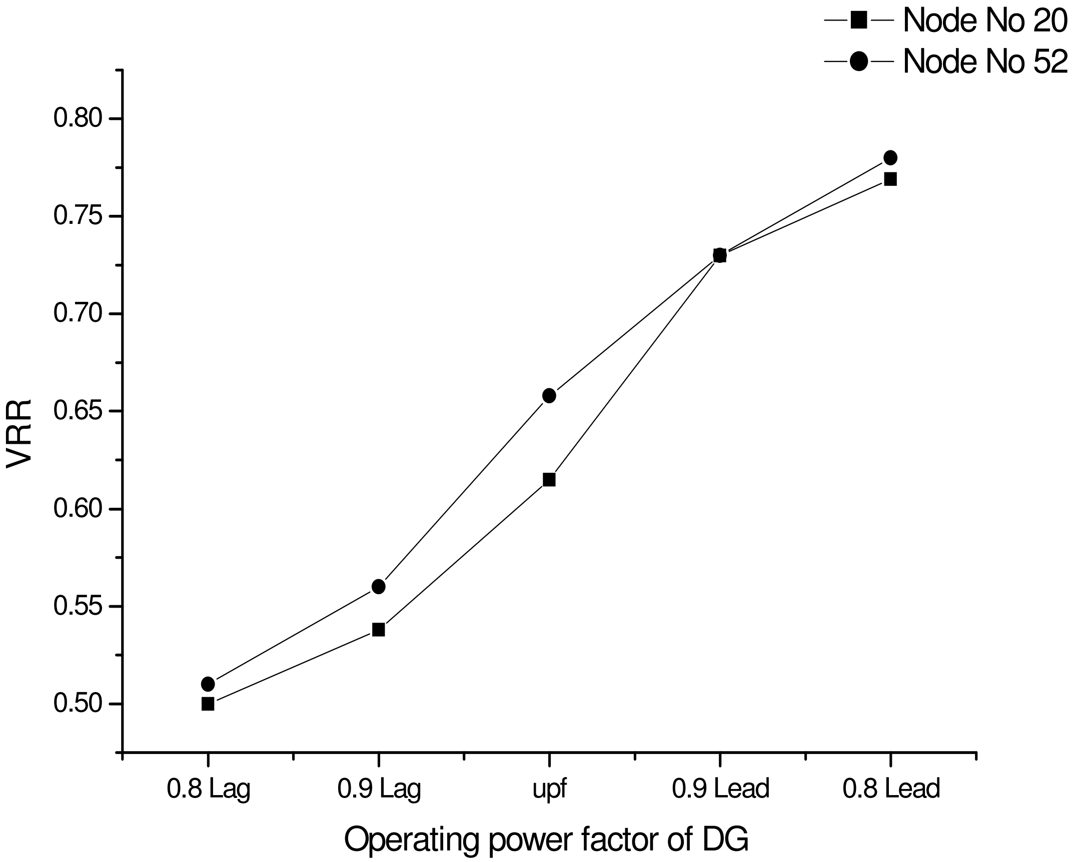


Fig. 6.13 Figure showing the effct of operating pf of DG on VRR

6.5 Estimation of Fault Location

In general, the estimation of fault location is obtained by measuring the voltages and currents at the substation. The presence of distributed generation greatly affects these values resulting in erroneous results because, when a fault occur, the main source will not have to supply as much power to the line, as it would have supplied in the absence of DG.

In this investigation, the method of impedance discussed in chapter IV, is used to estimate the location of the fault. A single line to ground fault is simulated and estimates are obtained. Two cases have been considered to evaluate the influence of DG on the estimation.

Case A:- A single line to ground fault at node No. 20, at a distance of 1.4 km from the substation.

Case B:- A single line to ground fault at node No. 48, at a distance of 3.23 km from the substation.

For each of these cases, the fault location estimates are obtained. The short circuit power of each DG unit is taken as 5 times the rated value. Both DG units are assumed to be operating at their rated values. Table 6.4 shows the substation voltages and currents for these cases, which are found to be influenced by the presence of DG considerably.

The estimated fault locations with and without DG, along with the % error are listed in table 6.5 for both the cases. It can be observed that, two estimates are obtained due to branched nature of the system. Figures 6.14 and 6.15 show the actual location and the estimated fault locations for the two cases. The % errors for the case 1, with various ratings of DG are plotted in figure 6.16.

It is observed the estimated locations, in the presence of DG, produce more errors than the estimates which were obtained without DG.

Table 6.4a: Table showing the measured values of voltages and currents at the substation without DG for a Single Line to Ground Fault in phase ‘a”, as described by cases A and B.

Case	Phase Voltages at substation without DG			Line Currents at substation without DG		
	Van (kV)	Vbn (kV)	Vcn (kV)	Ia (Amps)	Ib (Amps)	Ic (Amps)
Under healthy Conditions	6.3	6.3	6.3	104.2	104.2	104.2
Case A	1.1	7.9	7.2	4648	97.8	90.8
Case B	2.7	7.6	6.7	3469	97.3	89.7

Table 6.4a: Table showing the measured values of voltages and currents at the substations with DG for a Single Line to Ground Fault in phase ‘a”, as described by cases A and B with DG operating at rated conditions.

Case	Phase Voltages at substation with DG			Line Currents at substation with DG		
	Van (kV)	Vbn (kV)	Vcn (kV)	Ia (Amps)	Ib (Amps)	Ic (Amps)
Under healthy conditions	6.3	6.3	6.3	39.9	39.9	39.9
Case A	1.3	7.4	6.7	4879	-516	548.8
Case B	2.6	7.3	7.0	3384	250.1	181.8

Table 6.5. Table showing the estimated fault location with and without DG for both cases.

Actual Fault Location in km (Distance measured from substation)	Estimated Fault Location(km) without DG	% Error	Estimated Fault Location (KM) with DG	% Error
1.4	1.28	-2.5	1.22	-3.75
	1.35	-1.04	1.31	-1.875
3.23	3.10	-2.78	3.04	-3.958
	3.14	-1.875	3.06	-3.54

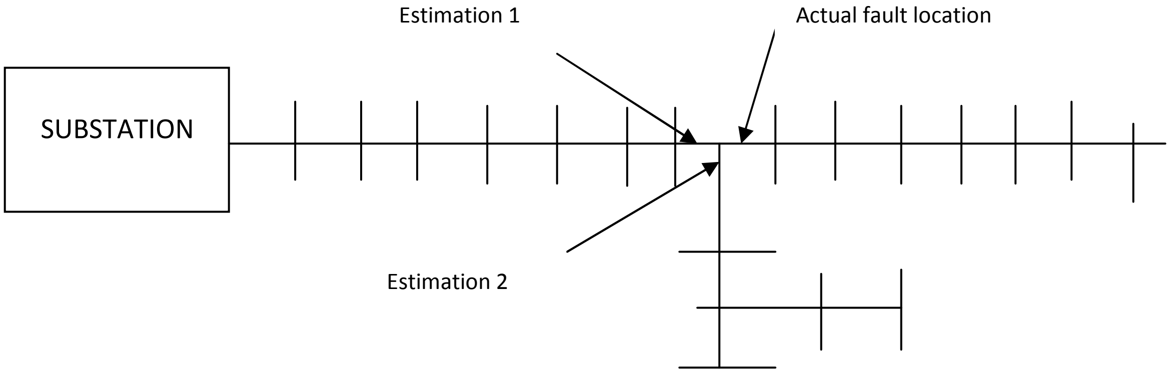


Fig. 6.14 Figure showing the enlarged portion of the feeder covering the exact location and the estimated locations with the presence DG for case A

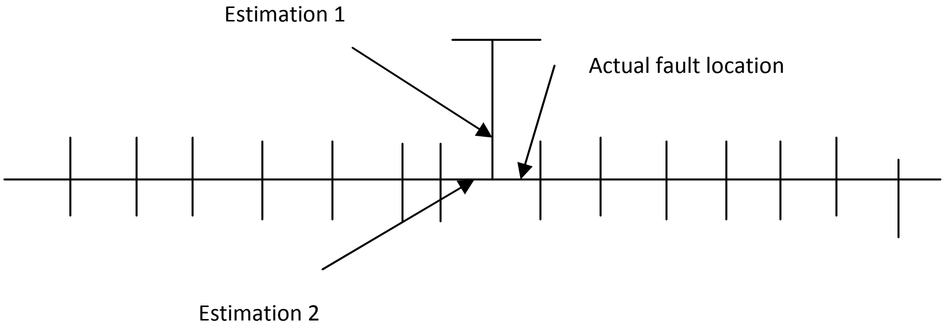


Fig. 6.15 Figure showing the enlarged portion of the feeder covering the exact location and the estimated locations with the presence DG for case B

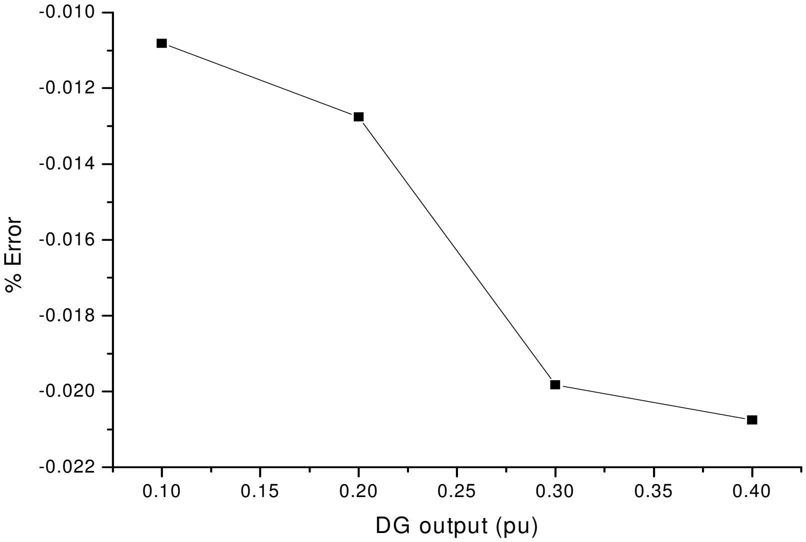


Fig.6.16. Figure showing the error as a function of DG output for the fault at node No. 20

It is observed that the error in the results obtained for the fault location using impedance method increase with the penetration of DG. It is therefore essential to consider the effect of DG and run the fault location algorithm as given in section 5.1.2.

6.6 Effect of Faults on Low Voltage side.

The rise in the line currents caused by the faults on the low voltage side is not very significant. Any such changes may be confused with the normal change in the current due to load variation. Especially with the inclusion of DG, this is of great importance.

In the present investigation, faults are simulated on the low voltage side at various points and the line currents on the high voltage sides are measured. Table 6.6, shows all the simulation results. It is evident from the table that the fault on LV side causes a least variation of substation current even without DG. The rise in current is extremely small and is not at all detected with the presence of DG.

Table 6.6 Table showing the substation Voltage and currents for faults on Low voltage side, with and without DG

	Van (Volts)	Vbn (Volts)	Vcn (Volts))	Ia (Amps)	Ib (Amps)	Ic (Amps)
Without Fault, Without DG	6300	6300	6300	104	104	104
Without DG, Fault at 23	6300	6300	6300	121	104.2	126.4
With DG, No Fault	6300	6300	6300	50.3	50.3	50.3
With DG, Fault at 23	6300	6300	6300	60.9	50.3	62.2

6.7 KVA delivered by the substation.

The most important benefit and common understanding of embedded generation is that substation delivers less power in the presence of DG than in the absence of DG. This is found to be partially true because, though the statement is true for active power, the same is not true for reactive power in the case when the DG is operating at a different power factor than that of the load. If the DG operates at unity OR leading power factor, the loads have to draw reactive power from the supply lines itself, thereby increasing the KVAR burden on the lines. Hence KVA is not proportionately reduced by the presence of DG. Table 6.7 show the active and reactive power supplied by both the main source and the DG units for different power factors of DG units. From the table it is very clear that even if a DG supplies one-third of active power of the load, the source has to deliver almost same KVA as it would have delivered in the absence of DG. This point has to be considered while fixing the operating power factor of DG. This issue is of great concern with solar pv generation since, the solar pv generation always operates at unity power factor.

Table 6.7 Details of power delivered by the Source and DG2 when the load demand is 1860 KVA at 0.8 pf lagging, with DG operating at various power factors.

Operating Power factor of DG2	Power injected by DG			Power supplied by the source		
	KW	KVAR	KVA	KW	KVAR	KVA
	0	0	0	1500	1100	1860
0.8 Lag	400	300	500	1166	890	1467
0.9 lag	400	193	444	1168	997	1535
Unity	400	0	400	1172	1193	1672
0.9 Lead	400	193 (lead)	444	1177	1390	1821
0.8 Lead	400	300 (Lead)	500	1180	1500	1908

CHAPTER 7

CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1 Concluding Remarks

The increasing demand for clean and quality energy has triggered the utilities to seek new technologies to provide reliable power to the consumers. The option of using distributed generation is being studied in almost all parts of the globe and is in practice in many western countries. DG units, powered by renewable energy resources have been proved to provide small power with less environmental impacts, thereby helping both utility and society in general.

Although many technologies exist for distributed generation, only two energy resources available locally are considered in this research. These are:

- Solar PV generation,
- Municipal Solid Waste fuelled power generation.

Solar insolation is random in nature. Hence probabilistic model is used to model pv generation. Beta distribution is employed for cloud cover which require mean and standard deviation of the cloud cover values. The power output of the pv panel is modeled in terms of this cloud cover.

The MSWFPG, can be modeled by knowing the quantum of waste which is available for incineration. This value is evaluated by knowing the waste collected and by knowing waste passing through various waste flow paths.

The introduction of DG into an existing distribution system has many potential benefits. These include the loss reduction, voltage profile improvement, deferral of investment in infrastructure extension, improvement in reliability etc. At the same time DG also gives rise to many issues like protection, stability etc. Out of many benefits only two benefits: loss reduction and voltage profile improvement and one issue on the protection side viz. the estimation of fault location are considered in this research. Accordingly two indices are proposed:

- System Loss Reduction Index (SLRI)and
- Voltage Regulation ratio (VRR).

The System Loss Reduction ratio (SLRI) is defined as the ratio of the loss occurring in the system with DG to that without DG. If SLRI is less than 1, the introduction of DG is beneficial to the system. SLRI is an improvement to the previously proposed LLRI, which does not consider the LV side losses and the core losses of the transformers. Similarly VRR is the ratio of the voltage regulation at any node with DG and that without DG at the same node. If VRR is less than 1, DG has improved the voltage profile.

The simulation results indicate that DG reduces the system losses and also improves the voltage profile. It is noticed that for increased penetration of DG, both the benefits also improve. However, this trend will not continue for higher penetration of DG. With very large penetration of DG, the system loss increase than decreasing and the voltage at certain nodes may be more than the rated value which is unwarranted.

Simulation results also indicate that the operating power factor and the location of DG also affect the SLRI and VRR. With the leading operating power factor of DG, the SLRI actually increase, thereby indicating the increase in loss. Similarly VRR also assumes negative values indicating increase in voltage values more than the rated value.

The inclusion of DG is found to affect the estimation of fault location. The common method of estimating the fault location is based on the impedance method which uses the fundamental components of voltages and currents measured at the substation. These values are found to vary with the high penetration of DG and give erroneous results of fault location.

The simulation also reveals that the operating power factor of DG unit has considerable effect on the reactive power delivered by the substation. If the DG is operating at unity power factor, the reactive power required by the loads will have to be drawn from the main source itself and therefore, there is no significant change in the KVA delivered by the main source.

The results obtained from the research will help in arriving at a suitable location and deciding a proper rating and power factor of the DG unit. The research also helps in deciding the output of solar PV generation. An important outcome of the research is that a freely available resource in any urban area: Municipal Solid Waste is tested and found to be suitable for power generation which also gives a solution for waste management issue.

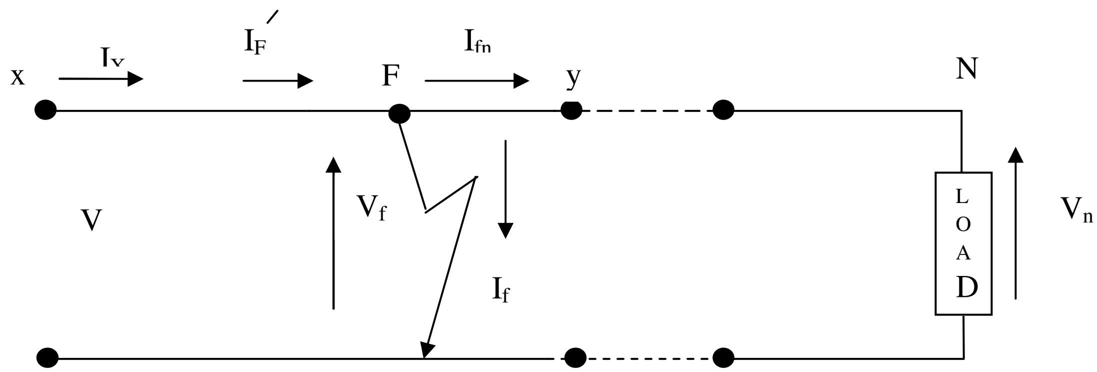
7.2 Scope for future work

Although this work is carried out to study the impacts of distributed generation on a practical distribution system, there are certain limitations in the research.

- The estimation of fault location needs further studies to include the effect of higher penetration of distributed generation.
- The issues arising out of the operating power factor of DG on the KVAR supplied by the source needs to be addressed and a power factor correction arrangements at the substation side needs investigation.
- The faults on the LV side are not usually noticed at the substations since the change in the current and voltage values at the substations are usually mistaken for the change in loads and therefore the faults may not be detected at all. This is more severe with high penetration of DG. This issue needs further analysis.
- This research has given only a snapshot consideration in connection with economic aspects of both the resources. The detailed economic analysis for the proposed DG resources should be carried out.

Appendix

Fault location algorithm based on Impedance method



From the figure, we observe that

$$\begin{bmatrix} V_f \\ I_f' \end{bmatrix} = \begin{bmatrix} 1 & -sB_{xy} \\ -sC_{xy} & 1 \end{bmatrix} \begin{bmatrix} V_x \\ I_x \end{bmatrix}$$

Where ‘s’ is the distance of the fault from the node ‘x’.

The voltage and current at ‘y’ is written as

$$\begin{bmatrix} V_y \\ I_y \end{bmatrix} = \begin{bmatrix} 1 & -(1-s)B_{xy} \\ -(1-s)C_{xy} & 1 \end{bmatrix} \begin{bmatrix} V_f \\ I_{fn} \end{bmatrix}$$

And the voltage and currents at the remote end are written as

$$\begin{bmatrix} V_n \\ I_n \end{bmatrix} = \begin{bmatrix} D_e & -B_e \\ -C_e & A_e \end{bmatrix} \begin{bmatrix} V_x \\ I_x \end{bmatrix}$$

Combining equations 1,2 and 3, we get,

$$\begin{bmatrix} V_n \\ I_n \end{bmatrix} = \begin{bmatrix} K_a + sK_b & K_c + sK_d \\ K_e + sK_f & K_g + sK_h \end{bmatrix} \begin{bmatrix} V_f \\ I_{fn} \end{bmatrix}$$

Where $K_a = D_e + B_e C_{xy}$, $K_b = - B_e C_{xy}$; $K_c = -(B_e + D_e B_{xy})$, $K_d = D_e B_{xy}$

and $K_e = C_e + A_e C_{xy}$, $K_f = A_e C_{xy}$; $K_g = A_e + C_e B_{xy}$; $K_h = - C_e B_{xy}$

Identifying $I_{fn} = I'_f - I_f$ and substituting in equation 4,

$$\begin{bmatrix} V_n \\ I_n \end{bmatrix} = \begin{bmatrix} K_a + sK_b & K_c + sK_d \\ K_e + sK_f & K_g + sK_h \end{bmatrix} \begin{bmatrix} V_f \\ I'_f \end{bmatrix} - \begin{bmatrix} K_a + sK_b & K_c + sK_d \\ K_e + sK_f & K_g + sK_h \end{bmatrix} \begin{bmatrix} 0 \\ I_f \end{bmatrix}$$

On simplification of equation 5, and identifying $I_n = y_n V_n$, we get

$$\begin{bmatrix} 1 & K_c + sK_d \\ y_n & K_g + sK_h \end{bmatrix} \begin{bmatrix} V_n \\ I_f \end{bmatrix} = \begin{bmatrix} K_a + sK_i & K_c + sK_j \\ K_e + sK_k & K_g + sK_l \end{bmatrix} \begin{bmatrix} V_x \\ I_x \end{bmatrix}$$

Where $K_i = (K_b - K_c C_{xy})$; $K_j = (K_d - K_a B_{xy})$;

and $K_k = (K_f - K_g C_{xy})$; $K_l = (K_h - K_e B_{xy})$

Simplifying we get,

$$\begin{bmatrix} V_n \\ I_f \end{bmatrix} = \frac{1}{K_V + sK_W} \begin{bmatrix} K_m + sK_n & K_D + sK_p \\ K_q + sK_r & K_v + sK_u \end{bmatrix} \begin{bmatrix} V_x \\ I_x \end{bmatrix}$$

Where, $K_v = (K_e - y_n K_e)$; $K_u = (K_l - k y_n)$; $K_D = (K_c - y_n K_a)$; $K_p = (j - y_n K_i)$

$K_m = K_a K_g - K_c^2$; $K_n = K_a K_h + K_i K_g - K_c K_d - K_c K_j$;

and $K_q = K_e K_g - K_c K_g$; $K_r = K_e K_n + K_k K_g - K_g K_d - K_c K_l$;

and $K_V = (K_g - y_n K_c)$; $K_W = (K_h - y_n K_d)$

The fault impedance $Z_f = \frac{V_f}{I_f} = \frac{V_{0f} + V_{1f} + V_{2f}}{I_{1f} + I_{1f} + I_{2f}} = R_f$

Hence $Im\left(Z_f\right) = 0$

Which can be expressed as $Im\left(\frac{K_A + sK_B}{K_C + s\,K_D}\right) = 0$

Where K_A, K_B, K_C and K_D are complex parameters, which are expressed into real and imaginary parts as

$K_A = K_{AR} + jK_{AI},$

$K_B = K_{BR} + jK_{BI}$

$K_C = K_{CR} + jK_{CI}$

$K_A = K_{DR} + jK_{DI}$

Substituting the values of the constants and simplifying, the value of‘s’ is obtained as

$$s = \frac{K_{AR} + K_{CI} - K_{AI} K_{CR}}{\left(K_{CR} K_{BI} - K_{CI} K_{BR}\right) + \left(K_{DR} K_{AI} - K_{DI} K_{AR}\right)}$$

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