Handbook of Research on Power and Energy System Optimization

Pawan Kumar
Thapar University, India

Surjit Singh
National Institute of Technology Kurukshetra, India

Ikbal Ali
Jamia Millia Islamia, India

Taha Selim Ustun
Carnegie Mellon University, USA

A volume in the Advances in Computer and
Electrical Engineering (ACEE) Book Series

IGI Global
DISSEMINATOR OF KNOWLEDGE

Published in the United States of America by
IGI Global
Engineering Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA, USA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

Names: Kumar, Pawan, 1977- editor. | Singh, Surjit, 1981- editor. | Ali, Ikbal, editor. | Ustun, Taha Selim, editor.
Title: Handbook of research on power and energy system optimization / Pawan Kumar, Surjit Singh, Ikbal Ali, and Taha Selim Ustun, editors.
Description: Hershey, PA : Engineering Science Reference, [2018] | Includes bibliographical references.
Identifiers: LCCN 2017024144| ISBN 9781522539353 (hardcover) | ISBN 9781522539360 (ebook)
Subjects: LCSH: Electric power systems--Management--Data processing--Handbooks, manuals, etc. | Electric power systems--Mathematical models--Handbooks, manuals, etc. | Mathematical optimization--Handbooks, manuals, etc.
Classification: LCC TK1005 .H29375 2018 | DDC 621.31--dc23 LC record available at https://lccn.loc.gov/2017024144

This book is published in the IGI Global book series Advances in Computer and Electrical Engineering (ACEE) (ISSN: 2327-039X; eISSN: 2327-0403)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

Chapter 1

Fuzzy-Logic-Based Reactive Power and Voltage Control in Grid-Connected Wind Farms to Improve Steady State Voltage Stability

Tukaram Moger
National Institute of Technology Karnataka, India

Thukaram Dhadbanjan
Indian Institute of Science Bangalore, India

ABSTRACT

This chapter presents a fuzzy logic approach for reactive power and voltage control in grid-connected wind farms with different types of wind generator units to improve steady state voltage stability of power systems. The load buses' voltage deviation is minimized by changing the reactive power controllers according to their sensitivity using fuzzy set theory. The proposed approach uses only a few high sensitivity controllers to achieve the desired objectives. A 297-bus-equivalent grid-connected wind system and a 417-bus-equivalent grid-connected wind system are considered to present the simulation results. To prove the effectiveness of the proposed approach, a comparative analysis is also carried out with the conventional linear-programming-based reactive power optimization technique. Results demonstrated that the proposed approach is more effective in improving the system performance as compared with the conventional existing techniques.

DOI: 10.4018/978-1-5225-3935-3.ch001

NOTATIONS

a: Transformer off-nominal tap
j: Complex operator
α: Angle of the primitive admittance of the line
y: Primitive admittance of the line
Y: Admittance matrix
B: Line charging susceptance
ΔQ: Incremental change in bus reactive power
ΔV: Incremental change in bus voltage magnitude
ΔT: Incremental change in transformer tap
θ: Angle of the bus admittance matrix
δ: Voltage phase angle
V^d_j: Desired voltage at load bus j
V^a_j: Actual voltage at load bus j
V^e: Error or difference voltage at load bus
V_{min}: Minimum or lower limit on bus voltage
V_{max}: Maximum or upper limit on bus voltage
X: Row vector of the voltage/reactive power controllers
$[C]$: Controlling ability of the controller matrix
m: Controller index
t_g: Number of grid OLTC transformers
t_{pcc}: Number of OLTC transformers at the point of common coupling of wind farm
g: Number of generators
svc: Number of switchable VAr compensators
$vswg$: Number of variable speed wind generators
r: Number of remaining buses
M: Voltage/reactive power controller step size
$[H]$: Voltage deviation sensitivity matrix
$[S]$: Linearized sensitivity matrix relating dependent and control variable
L-index: Static voltage stability index
n: Number of total buses
P_{loss}: System active power loss
Q_{loss}: System reactive power loss
L^{max}-*index*: Maximum value of voltage stability index

ABBREVIATIONS

AC: Alternating current
DFIG: Doubly fed induction generator
FERC: Federal energy regulatory commission
FLA: Fuzzy logic approach
FSWG: Fixed speed wind generator

GSC: Grid side converter
kV: Kilo volt
LP: Linear programming
MVAr: Mega volt ampere reactive
MVA: Mega volt ampere
MW: Mega watts
NL: Negative large
NLP: Non linear programming
NM: Negative medium
NS: Negative small
NVL: Negative very large
OLTC: On load tap changing transformer
OPF: Optimal power flow
PCC: Point of common coupling
P-V: Power-voltage
PR-FSWG: Pitch regulated fixed speed wind generator
pu: Per unit
pf: Power factor
PF: Power flow
PL: Positive large
PM: Positive medium
PS: Positive small
PVL: Positive very large
RSC: Rotor side converter
SCIG: Squirrel cage induction generator
SGFEC: Synchronous generator with front end converter
SR: Southern region
SR-FSWG: Stall regulated fixed speed wind generator
SSWG: Semi-variable speed wind generator
STDEV: Standard deviation
SVC: Switchable VAr compensator
VAr: Volt ampere reactive
V: Voltage
VSWG: Variable speed wind generator
UPF or UPF: Unity power factor
VS-WTGU: Variable speed wind turbine generating unit
VSC: Voltage source converter
WF: Wind farm
WGU: Wind generator unit
WTGU: Wind turbine generating unit
Z: Zero

INTRODUCTION

In recent years, the electric power industry around the world is changing continuously due to transformation from regulated market structure to deregulated market structure. The main aim of the transformation of electric supply industry under open access environment is to overcome the some of the limitations faced by a vertically integrated system. It is believed that this transformation will bring new technologies, and integration of other sources of energy or unconventional energy sources such as wind, solar, fuel cells, bio-gas, etc., which are self-sustainable and competitive. Moreover, it will also give better choice for the consumers. As a result, several new issues and challenges have emerged. One of the main issues in power systems is to support reactive power for maintaining the system voltage profile with an acceptable margin of security and reliability required for system operation.

In recent years, it has been observed that the voltage instability problem is the root cause for several major network blackouts in different countries such as France, Belgium, Sweden, Germany, Iran, Japan, USA and India (FERC, 2005; Srivastava, Velayutham, Agrawal, & Bakshi, 2012; Ajjarapu & Lee, 1998). Therefore, the system operator must make sure that there are enough reactive power reserve capacities available for the system to maintain the voltage profiles. Properly planned reactive power reserves minimize the risk of voltage collapse or low voltages as well as reduce transmission loss by keeping the appropriate voltage profiles (Elgerd, 1982; Taylor, 1994).

With concerns relating to climate change, energy prices, supply uncertainties and other factors, there is an increasing focus on renewable energy sources to satisfy energy requirements. Among the renewable energy resources, wind energy is gaining prominence due to the available technologies that allow for large scale power generation. Hence, the share of wind power in relation to the overall installed capacity has increased significantly. As wind energy installations are rapidly growing worldwide, the system operators are more concerned about the planning and operation of the system with wind farms.

The transmission grid code (Wu, Xu, & Østergaard, 2010; Tsili & Papathanassiou, 2009) in many countries requires wind farms to supply not only active power but also reactive power to the power grid. The grid code also specifies the reactive power ranges for wind generators as different types of wind generators will have different reactive power capability. The grid code regulations for reactive power/power factor requirements of wind farms in the system under steady state operating condition in some of the countries is summarized in Table 1.

Due to stochastic nature of wind, the wind farms adversely affect the voltage of the grid. It is necessary to control the load buses voltage and reactive power in the system so that the power quality of grid connected wind farms is maintained within the acceptable limits. Therefore, the reactive power and voltage control in grid connected wind farms is one of key issues that grid operators are concerned with, and received great attention from the researchers in recent years.

Presently, various types of WTGUs have been installed in the wind farms and can be broadly classified into two types, namely, fixed speed wind generators (FSWGs) which include both fixed and semi-variable speed type wind generators, and variable speed wind generators (VSWGs) which include doubly fed induction generator (DFIG) and synchronous generator with front end converter (SGFEC). The fixed speed wind generators are used in earlier wind farms installations. The lack of voltage or power factor regulation features in the FSWGs makes it difficult to operate these units with the grid as per the grid code requirements. To address these issues, researchers in the past have proposed several approaches/models to utilize the features of the FSWG in the system operation and make it compatible with the grid code requirements (Moger & Dhadbanjan, 2017). The fixed speed wind generators are

Table 1. Summary of existing grid code for reactive power/power factor requirement of wind farms

Country	Reactive Power/Power Factor Requirement		
	Max. Q Limit (Injection Limit)	Min. Q Limit (Absorption Limit)	Remarks
India (CERC, 2010)	0.95 lagging	0.95 leading	
UK (NGET, 2009)	0.95 lagging	0.95 leading	
US (FERC, 2005, 2012)	0.95 lagging	0.95 leading	
Alberta (Canada, 2004)	0.90 lagging	0.95 leading	
China (China, 2009)	0.97 lagging	0.97 leading	
Spain (Spain, 2005)	0.98 lagging	0.98 leading	Without any penalty
Ireland (EirGrid)	0.95 lagging	0.95 leading	
Australia (Australia, 2007)	1.0 UPF	0.95 leading	For 100% power
Germany (Germany, 2006)	0.95 lagging	0.95 leading	For capacity < 100 MW
	Voltage dependent reactive power limit for capacity > 100 MW		

Wu et al., 2010; Tsili & Papathanassiou, 2009.

of conventional asynchronous machine, which do not have capability to control the voltage, but rather absorbs large levels of reactive power during the normal operation. However, due to advancement in power electronics converter design, the variable speed wind generators have the ability to control the active and reactive power independently, and could be able to meet the grid code requirements. Hence, it is feasible to consider variable speed wind generators as possible sources of reactive power.

The growing importance of reactive power planning in the network has drawn the attention of system expansion planners to consider this important aspect of the resource planning. Reactive power controlling devices are being installed in transmission and distribution networks to enhance their operational efficiency in terms of better voltage profile, voltage control, increased power flow, and flexibility of power control and enhancing the stability of the system. These reactive power controls are scattered throughout the transmission network and are to be operated in coordination.

Judicious dispatch of reactive power is essential for the stable operation of the power system. It facilitates the flow of active power from generation sources to load centers (Kundur, Balu, & Lauby, 1994; Taylor, 1994) and maintains the bus voltages within prescribed limits (Abed, 1999). Stable operation of power systems requires the availability of sufficient reactive power generation in the system.

BACKGROUND

The integration of wind farms with power systems is taking place both at the transmission and distribution voltage levels. Several integration issues are also reported in the literature. The performance of grid connected wind turbine generating units could be quite different from the one that is operating in isolation (at nominal voltage and frequency). This is because the grid voltage and frequency fluctuate around the nominal value and hence, it is necessary to study the impact performance of the wind turbine generating units when connected to the grid to ensure the secure and reliable operation of the systems. These impacts can be positive or negative depending on the system operating characteristics and wind turbine generator itself (Trichakis, Taylor, Lyons, & Hair, 2008). Therefore, it is necessary to carry out an intensive research for reactive power and voltage control of wind farms, and review the related compensation facilities and strategies in order for the wind farms to be able to participate in grid voltage control and subsequently increase the grid stability.

The impact of wind generating units (WGUs) on various system aspects have been studied in the literature particularly the voltage stability of the system under steady state as well as transient conditions.

Vittal et al. (2010) investigated the impact of variable speed wind turbine generators on steady state voltage stability of the system. The voltage stability margin of both the distribution level and transmission level buses in the system can be increased through the proper implementation of voltage control strategies in the DFIG wind turbines. Freitas et al. (2005) investigated the long-term or small disturbance voltage stability of distribution systems with squirrel cage induction generators (SCIG) by using time-domain nonlinear dynamic simulations. The system stability margin is analyzed through the P-V curves. The system voltage stability margin may reduce due to the presence of SCIG. Usually, at the maximum loading point, if the system loading is increased even more, then the induction generator accelerates to a high speed and becomes unstable, which leading the system to a voltage collapse. Hossain et al. (2012) investigated the behavior of SCIG and DFIG on short-term voltage stability. Ullah and Thiringer (2007) proposed the improvements in grid voltage stability and transient stability with variable speed wind turbine generators using power electronics based converter with modified controller design. The voltage source converter (VSC) in modern variable speed wind turbine generators is utilized to achieve this enhancement. The suggested modifications can be incorporated in real installations through which the short-term voltage stability is improved as an additional feature of an existing VSC for the high voltage direct current (HVDC) installation.

As per the federal energy regulatory commission (FERC) order 661-A on interconnection requirements (FERC, 2005, 2012), the wind farm of capacity more than 25 MW should maintain the power factor range of 0.95 leading and lagging at the point of common coupling to the grid. Due to which, the reactive power capability of wind farms is drastically under-utilized. Fully utilizing the reactive power capability of DFIG wind farm in voltage control produces the significant improvements in the system performance and may prevent system voltage instability. Even though the FERC order 661-A gives general guidelines for interconnecting wind parks, but for specific parks employing DFIG units, the restriction on power factor can be lifted for enhancing the system voltage stability. In this connection, Konopinski et al. (2009) discussed the impact of utilizing reactive power capability curve of a doubly fed induction generator on steady state and dynamic power system operation.

Vittal et al. (2008) identified the ratio of DFIG wind turbine generators to fixed speed wind turbine generators required to maintain voltage and frequency stability during steady state and single line contingencies cases in the system. Further, authors discussed the effect of change in wind power generation and control strategies on system voltage profile (Vittal, O'Malley, & Keane, 2009) and voltage stability. P-V curve analysis was employed to demonstrate the improvement in voltage stability attained using terminal voltage control. In addition, other approaches are proposed to utilize the flexibility in reactive power generation of DFIG to reduce system losses (Meegahapola, Durairaj, Flynn, & Fox, 2011) and improve the reliability in static and dynamic system operation (Konopinski, Vijayan, & Ajjarapu, 2009). Chen et al. (2012) presented a coordinated reactive power and voltage control for wind farm gird integration to meet the operation requirements as described in the standards of state grid corporation of China. The control strategy of the proposed system takes into account the coordination between the voltage and power factor. The authors Kayikci and Milanovic (2007) discussed the different combinations of reactive power control of rotor side converter (RSC) and grid side converter (GSC) for voltage control purposes with the various network parameters and operation regimes. Chen et al. (2009) proposed a reactive/voltage control strategy of a wind farm to improve the voltage stability of the wind farm, but only one wind farm is considered. For a network integrating several large wind farms, how to improve the voltage stability by coordinating the reactive power among the wind farms is seldom reported in the literature. Aghatehrani et al. (2009) proposed a coordination method using both the rotor side and the grid side converters for voltage regulation and reactive power support considering the operational limits and network side voltage fluctuation. The central idea is to derive the reactive power reference signal in the rotor side converter (RSC) control loop from the terminal voltage controller in the grid side converter (GSC) control loop. Zhu et al. (2009) proposed a reactive power compensation control method considering voltage and reactive power command in integrated region. The voltage at the point of interconnection is chosen as controlled voltage and the related reactive power control is divided into three sections, namely, normal control, abnormal control and urgent control, which can be chosen according to detailed operation status of the system. Zheng et al. (2013) proposed a coordinated voltage control strategy using the sensitivity method. The coordinated reactive power and voltage control of wind farms is divided into two control hierarchies. In primary control, each wind farms regulate the voltage reference value at the point of interconnection of wind farm, and while in secondary control, the control center of wind farms give the values of voltage reference and reactive power adjustment. With the reactive power adjustment value of the wind farms based on sensitivity matrix, the voltage at the point of interconnection of the wind farms is adjusted to the reference value if it is exceeding the allowable range.

Most of the approaches reported in the literature (Keane, Ochoa, Vittal, Dent, & Harrison, 2011; Aghatehrani, Fan, & Kavasseri, 2009; Zhu, Chen, Wang, & Zhu, 2009) studied the impact of variations in reactive power output of variable speed wind generators (VSWGs) on voltage stability of the systems in isolation. Significant improvements in voltage stability can be attained if the reactive power output of the VSWGs is properly coordinated with other reactive power controllers in the grid. To achieve the reactive power requirement of the system in an optimal manner, grid operators may perform reactive power optimization within their own facilities. Some optimization based approaches have been reported in the literature (Meegahapola, Durairaj, Flynn, & Fox, 2011; Kumar, Reddy, & Dhadbanjan, 2014) for optimally dispatching reactive power to improve the voltage profile in grid connected wind farms.

De Almeida et al. (2006) proposed an optimized dispatch control strategy for active and reactive powers delivered by a doubly fed induction generator in a wind park. The control strategy used at the wind generator level exploits a combination of pitch control and control of the static converters to adjust the rotor speed for the required operating points. The optimization procedure is able to minimize the deviation between the total active and reactive power delivered by the wind farms as required by the system operator. Kumar et al. (2014) proposed a trust region framework for coordinating the reactive power output of VSWGs with other reactive power controllers in the grid for enhancement of system voltage stability and voltage profiles. However, the studies were carried only considering the VSWGs in the wind farms. In practical wind farms, the fixed speed wind generators are also present. The studies in the literature show that the fixed speed wind generating units have significant impact on system voltage performance (Moger & Dhadbanjan, 2017; Divya & Rao, 2006). This is due to the requirement of reactive power support from the grid especially during low voltage conditions. Hence, it must be considered while coordinating the reactive power output of VSWGs with other reactive power controllers in the grid.

In the last few decades, more attention was paid to reactive power and voltage control in power systems to improve the system voltage profile. The reactive power and voltage control is a subset of the optimal power flow (OPF) problem, which seeks to find an optimal set of parameters for steady state power system operation. It is a constrained, nonlinear problem of considerable complexity. Since the problem of reactive power optimization is non-linear in nature, non-linear programming (NLP) methods have been used to solve it. The NLP methods work quite well for small power systems but may develop convergence problems as system size increases. The studies performed on some IEEE standard test systems (Pudjianto, Ahmed, & Strbac, 2002) show that NLP based optimal power flow is comparatively less robust with respect to convergence under all the random starting points. A bad initial point, for instance near any operating limit of control and/or state variables, as well as a too narrow operating range of control or state variables may limit the permissible step length for those variables and therefore restrict the movement of the other variables. This would then cause non-convergence of the NLP based OPF. Linear programming technique with iterative scheme is certainly the most promising tools for solving these types of problems (Dhadbanjan, Parthasarathy, & Prior, 1984; Dhadbanjan & Yesuratnam, 2006).

In the context of real-time operation, the voltage stability analysis should be performed online. The conventional algorithms or approaches (Lof, Andersson, & Hill, 1993) such as linear programming (LP) require significant computation time as it uses all the controllers to achieve the desired objectives. For online applications, there is a need for tools which can quickly detect the potentially dangerous situations of voltage instability and provide guidance to the operators to steer the system away from a possible voltage collapse. Tinney et al. (1988) stated that there is no way to select a subset of the most important control actions from the total set of control actions in the conventional OPF solution since the actions are not ranked and importance of an action is not necessarily related to its magnitude. Therefore, conventional optimization problem uses all of the controllers to achieve the desired objectives. Researchers have explored other possibilities like fuzzy logic, expert systems and so on to address the issues of concern.

Recently, the efforts to improve the speed and ability to handle stressed power systems have led to the development of intelligent systems. Recent developments indicate that artificial intelligence techniques like fuzzy logic (Su & Lin, 1996; Bansal, 2003; El-Hawary, 1998), artificial neural networks (Scala, Trovato, & Torelli, 1996; El-Keib & Ma, 1995; Niebur, 1993) and expert systems (Dhadbanjan, Bansilal, & Parthasarathy, 1997; Dhadbanjan & Parthasarathy, 1995) and so on, may be appropriate for assisting the operators for real-time operation.

In recent years, many applications of fuzzy set theory to reactive power control problem have been reported in the literature (Su & Lin, 1996; Yokoyama, Niimura, & Nakanishi, 1993; Abdul-Rahman & Shahidehpour, 1993; Marques, Taranto, & Falc˜ao, 2005). In all these applications of fuzzy set theory to reactive power control problem, the objectives are to either minimize real power losses or improve the voltage profile of the given system.

Tomsovic (1992) proposed a fuzzy linear programming approach to reactive power and voltage control problem. Here, the objective and constraints are modeled using fuzzy sets and corresponding linear membership functions are defined and solved using LP technique. Udupa et al. (1999) presented an approach using fuzzy set theory for reactive power control with the purpose of improving the voltage stability of power systems. The voltage stability index (*L-index*) and controlling variables are translated into fuzzy set notations to formulate the relation between the voltage stability level and controlling ability of controlling devices using the linearized model. Then, fuzzy rule based system is formed to achieve the desired goal. Su and Lin (2001) presented an approach using fuzzy set theory for voltage and reactive power control of power systems. The purpose is to find a solution, which takes both voltage security enhancement and loss reduction into account for an electric power system. The proposed approach translates violation level of buses voltage and controlling ability of controlling devices into fuzzy set notations using linearized model. Nageswararao and Jeyasurya (1998) presented a fuzzy expert system approach to steady state voltage stability monitoring and control in power systems. In the proposed rule based expert system, a systematic procedure for voltage stability monitoring and control is developed. The key variables are the load bus voltage, generator MVAr reserve and generator terminal voltage. The three key variables (which have significant impact on the system performance) are selected based on the solution obtained by repeated load flow and modal analysis performed for various operating conditions. The information from the above analysis is stored in a knowledge base. A set of decision rules relating key system variables to voltage stability are established. The membership functions of the key variables and fuzzy rules may be defined based on the system requirements and operators experience. The designed expert system performs voltage stability monitoring and control through deductive reasoning. Tang et al. (1993) presented an expert system for voltage correction in interconnected power systems. As the control variables such as shunt capacitors and reactors, OLTC transformers are discrete, an algorithm for heuristic, one dimensional search in a discrete state space of control variables is proposed. The search is based on a heuristic function, which takes both the priority and the regulation effect of control variables into account. Shareeq et al. (2014) proposed a fuzzy rule based approach for addressing the reactive power and voltage control of grid connected wind farms. In the proposed approach the wind turbine generators are modeled as PV buses and therefore, the voltage of the wind turbine generators is considered as control variables in the reactive power optimization process. Further, Moger and Dhadbanjan (2016) proposed a new procedure in the fuzzy logic approach to address the issues associated with various controllers in grid connected wind farms. The FSWGs are also considered in the studies because of its impact on overall system voltage performance even though they do not support the system for voltage unlike the VSWGs (Moger & Dhadbanjan, 2017).

OBJECTIVES AND CONTRIBUTION

This chapter presents a fuzzy logic approach for reactive power coordination in grid connected wind farms with different types of wind generator units (wind farms with different wind generator types i.e., FSWGs and VSWGs) for the purpose of improving the steady state voltage stability of power systems. The load buses voltage deviation is minimized by changing the controllers according to their sensitivity. The control variables considered are switchable VAr compensators (SVCs), on load tap changing (OLTC) transformers, generator excitations and reactive power output of the VSWGs. The approach translates bus voltage violation and controlling ability of controlling devices (controllers) into fuzzy set notations using linearized model. Then, fuzzy rule based system is formed based on the operator's experience to select the important controllers to meet the desired objectives. The FSWGs are also considered in this study because of its impact on overall system voltage performance even though they do not support the system for voltage unlike the VSWGs. A 297-bus equivalent grid connected wind system and a 417-bus equivalent grid connected wind system are considered to present the simulation results. A comparative analysis is also carried out with the conventional LP based reactive power optimization technique to highlight the features of the proposed approach.

METHODOLOGY

The main objective of this work is to reduce the voltage deviation at the load buses by reactive power redistribution in the system. This can be achieved by adjusting the OLTC transformers tap, generator excitations, SVCs and reactive power output of the VSWGs. The problem can be stated in mathematical form as,

$$V^{e} = \sum_{j=g+1}^{n} \left[V_{j}^{d} - V_{j}^{a}\right]^{2} \tag{1}$$

where,

V^{d}_{j} is the desired voltage at load bus *j*, which can be considered as nominal voltage (1.0 p.u) and
V^{a}_{j} is the actual voltage at load bus *j*.

For effective implementation of the proposed approach in grid connected wind farms, the total reactive power controllers in a particular types/groups (i.e., transformers or reactive power output of the elements) are separated into the subgroups depending on their power rating or capacity. In case of OLTC transformers, two separate subgroups are formed. In one subgroup only grid OLTC transformers are present, and another subgroup comprises of OLTC transformers at the point of common coupling (PCC) of wind farms since these have their power rating or capacity much lower than the grid OLTC transformers. Similarly, the SVCs are in one subgroup and VSWGs are in another subgroup.

Calculation of Controlling Ability of the Controllers

Consider a grid connected wind system comprising of *n* number of total buses. Let *g* be the number of grid generator buses, t_g be the number of grid OLTC transformers, t_{pcc} be the number of transformers at the PCC of wind farms, *svc* be the number of SVC buses, *vswg* be the number of VSWG buses, and *r* be the remaining buses.

Let *X* be the row vector of the voltage/reactive power controllers in the system and C_{jm} be the controlling ability of the controller X_m on j_{th} load bus. The controlling ability of the controller C_{jm} can be defined as,

$$C_{jm} = H_{jm} \times M_{m} \tag{2}$$

where,

m is the controller index ($m = 1, \ldots t_g; t_g + 1, \ldots t_g + t_{pcc}; t_g + t_{pcc} + 1, \ldots t_g + t_{pcc} + g; t_g + t_{pcc} + g + 1, \ldots t_g + t_{pcc} + g + svc; t_g + t_{pcc} + g + svc + 1, \ldots t_g + t_{pcc} + g + svc + vswg$),
M_m is the margin available for controller X_m, and
H_{jm} is the sensitivity of the controller X_m with respect to the j_{th} load bus.

$$H_{jm} = \frac{\partial V_j^e}{\partial X_m} = 2\left(V_j^d - V_j^a\right)\left(-S_{jm}\right) \tag{3}$$

where,

$V^e_j = (V^d_j - V^a_j)$ is the voltage error to be corrected at j^{th} load bus, and
S_{jm} is the linearized sensitivity factor of load bus j with respect to the controller X_m.

Computation of Sensitivity Matrix ([*S*])

The sensitivity matrix [*S*] relating the dependent and control variables is evaluated (Dhadbanjan et al., 1984; Dhadbanjan & Yesuratnam, 2006) in the following manner. It is known that the reactive power injection at a bus does not change for a small change in the phase angle of bus voltage. Based on this assumption, the relationship between the net reactive power change at any node due to change in the transformer tap settings and voltage magnitudes can be written as,

$$\begin{bmatrix} \Delta Q_g \\ \Delta Q_{svc} \\ \Delta Q_{vswg} \\ \Delta Q_r \end{bmatrix} = \begin{bmatrix} \frac{\partial Q_g}{\partial T_{t_g}} & \frac{\partial Q_g}{\partial T_{t_{pcc}}} & \frac{\partial Q_g}{\partial V_g} & \frac{\partial Q_g}{\partial V_{svc}} & \frac{\partial Q_g}{\partial V_{vswg}} & \frac{\partial Q_g}{\partial V_r} \\ \frac{\partial Q_{svc}}{\partial T_{t_g}} & \frac{\partial Q_{svc}}{\partial T_{t_{pcc}}} & \frac{\partial Q_{svc}}{\partial V_g} & \frac{\partial Q_{svc}}{\partial V_{svc}} & \frac{\partial Q_{svc}}{\partial V_{vswg}} & \frac{\partial Q_{svc}}{\partial V_r} \\ \frac{\partial Q_{vswg}}{\partial T_{t_g}} & \frac{\partial Q_{vswg}}{\partial T_{t_{pcc}}} & \frac{\partial Q_{vswg}}{\partial V_g} & \frac{\partial Q_{vswg}}{\partial V_{svc}} & \frac{\partial Q_{vswg}}{\partial V_{vswg}} & \frac{\partial Q_{vswg}}{\partial V_r} \\ \frac{\partial Q_r}{\partial T_{t_g}} & \frac{\partial Q_r}{\partial T_{t_{pcc}}} & \frac{\partial Q_r}{\partial V_g} & \frac{\partial Q_r}{\partial V_{svc}} & \frac{\partial Q_r}{\partial V_{vswg}} & \frac{\partial Q_r}{\partial V_r} \end{bmatrix} \begin{bmatrix} \Delta T_{t_g} \\ \Delta T_{t_{pcc}} \\ \Delta V_g \\ \Delta V_{svc} \\ \Delta V_{vswg} \\ \Delta V_r \end{bmatrix} \tag{4}$$

The sub-matrices $\partial Q / \partial T$ and $\partial Q / \partial V$ are the partial derivatives and the values are calculated from the following equations;

$$\frac{\partial Q_k}{\partial T_{kl}} = \frac{2}{a^3} V_k^2 y_{kl} \sin(\alpha_{kl}) + \frac{1}{a^2} y_{kl} V_k V_l \sin\left(\delta_k - \delta_l - \alpha_{kl}\right) \tag{5}$$

$$\frac{\partial Q_l}{\partial T_{kl}} = \frac{1}{a^2} y_{kl} V_k V_l \sin\left(\delta_l - \delta_k - \alpha_{kl}\right) \tag{6}$$

where,

k and *l* are the nodes to which OLTC transformer is connected and *k* is the tap side bus.

$$\frac{\partial Q_r}{\partial T_{kl}} = 0, \quad r \neq k, l \tag{7}$$

$$\frac{\partial Q_k}{\partial V_k} = \frac{Q_k}{V_k} - B_{kk} V_k \tag{8}$$

$$\frac{\partial Q_k}{\partial V_l} = Y_{kl} V_k \sin\left(\delta_k - \delta_l - \theta_{kl}\right) \tag{9}$$

where, *a* is the transformer tap; *y* is the primitive admittance of the line; *α* is the angle of the primitive admittance of the line; *Y* is the admittance matrix; *θ* is the angle of the bus admittance matrix; δ is the voltage phase angle; *B* is the line charging susceptance.

Further, transferring all control variables to the right hand side and the dependent variables to the left hand side, and rearranging the equations, we can get,

$$\begin{bmatrix} \Delta Q_g \\ \Delta Q_{svc} \\ \Delta Q_{vswg} \\ \Delta V_r \end{bmatrix} = \left[S\right] \begin{bmatrix} \Delta T_{t_g} \\ \Delta T_{t_{pcc}} \\ \Delta V_g \\ \Delta V_{svc} \\ \Delta V_{vswg} \end{bmatrix} \tag{10}$$

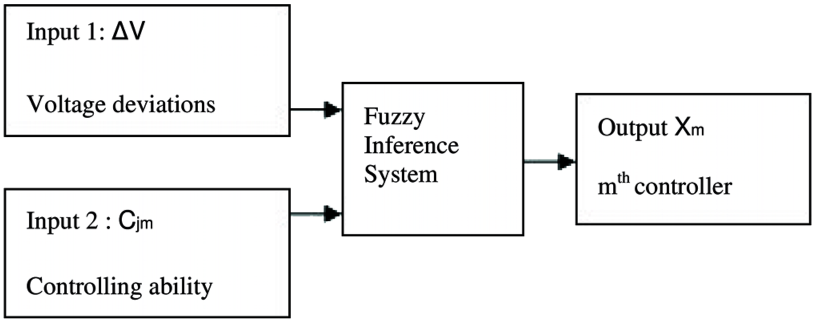
where [*S*] is the linearized sensitivity matrix relating dependent and control variables.

For all critical load buses, the most effective controller from each group is obtained based on the controlling ability of the controller's value from (2). The number of suggested steps for each controller can be obtained using fuzzy logic approach as explained in the following section.

Fuzzy Logic Approach

The main objective of using fuzzy logic approach (FLA) is to incorporate the experience of a power system operator in the design of control strategy to improve the system voltage profile. From a set of linguistic rules which describe the operator's control strategy, a control algorithm is constructed where the words are defined as fuzzy sets. The block diagram of fuzzy logic system for the proposed approach is given in Figure 1. The main advantage of the fuzzy logic approach seems to be the possibility of implementing rule of the thumb experience, intuition, and heuristics. The control strategies employed by an operator are formulated as a set of rules that are simple to carry out manually but difficult to implement by using conventional algorithms (Zadeh, 1965; Yager & Zadeh, 2012; Zimmermann, 2011). This is because human beings use qualitative rather than quantitative terms when describing various decisions to be taken as a function of different states of the process.

Figure 1. Block diagram of fuzzy logic system



Input and Output Parameters

The fuzzy logic technique is formulated using membership functions for the input parameters such as voltage deviation (ΔV) at each of the load buses and the voltage deviation sensitivity to control variables that is, controlling ability of the controllers ($[C]$). The voltage deviation (ΔV) for a load bus j is defined as,

$$\Delta V_j = V_j^a - V_j^d \tag{11}$$

These input parameters are transformed into fuzzy set notations with the help of membership functions. The membership function for the voltage deviation and controlling ability of the controller with linguistic variables are shown in Figures 2 and 3 respectively.

Figure 2. Membership function for the voltage deviation

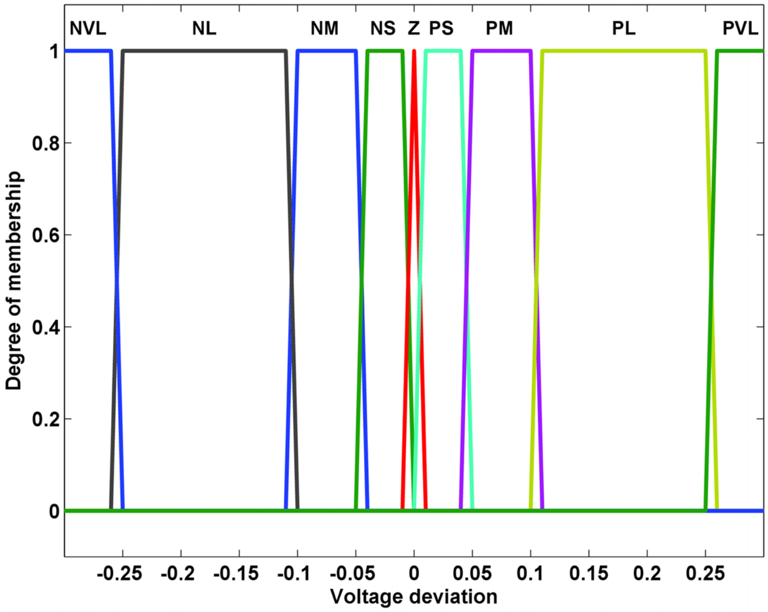
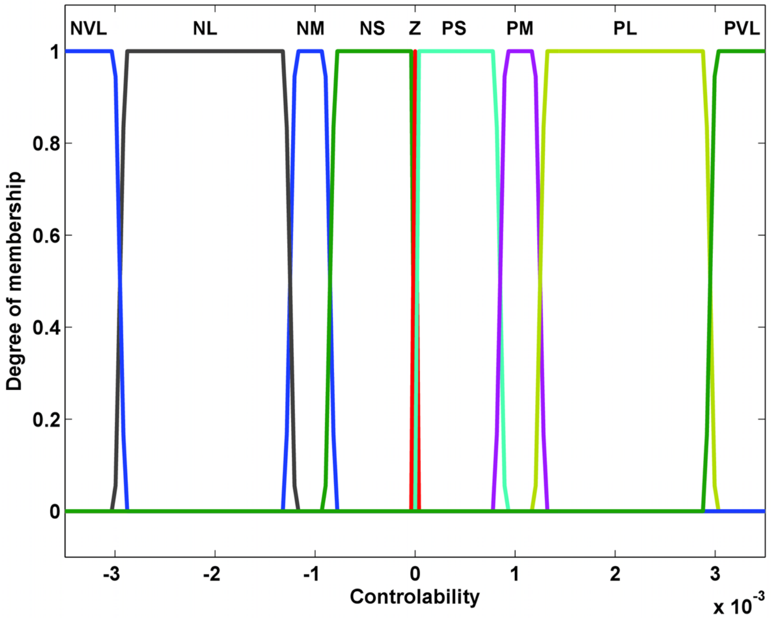
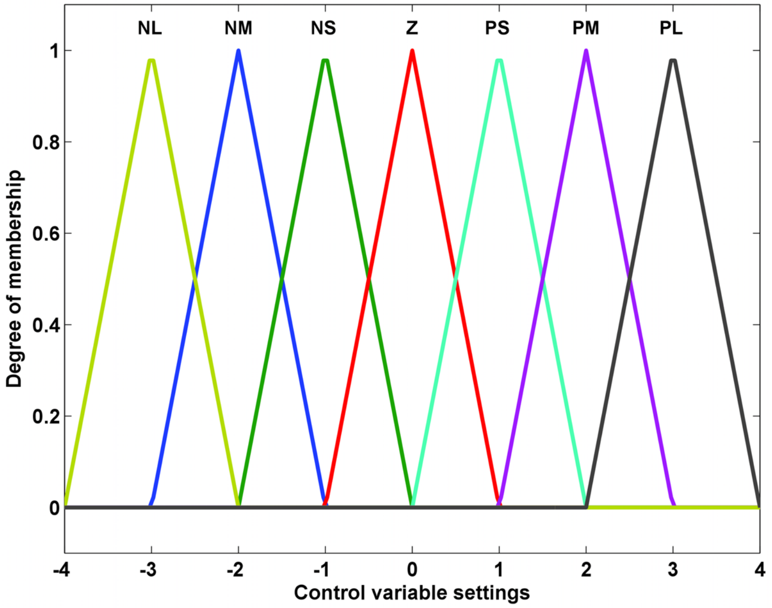


Figure 3. Membership function for the controlling ability of the controller



The output of fuzzy logic system is the new settings of the control variables such as grid OLTC transformers tap position, OLTC transformers tap position at the point of common coupling of the wind farms, generators excitation settings, switchable VAr compensator settings, and reactive power output of the VSWG settings. The membership function for the output with linguistic variables is shown in Figure 4.

Figure 4. Membership function for the controller settings



Definition of Fuzzy State Descriptions

The linguistic variables are used to describe the states of the systems. Nine linguistic variables are used for defining voltage deviation and controlling ability of the controller. The meaning of the linguistic variables are negative very large (NVL), negative large (NL), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive large (PL) and positive very large (PVL). Similarly, seven linguistic variables are used for defining the output, which are negative large, negative medium, negative small, zero, positive small, positive medium, and positive large.

Design of Fuzzy Rule

A rule based system consisting of 81 rules is developed to represent various system conditions, which is given in Table 2. Some of the control rules as fuzzy conditional statements of the type are described below. The number of steps in modifying the controller settings is limited to three. The implications or interpretations of the fuzzy output are given in Table 3.

- IF ΔV_j is PVL and C_{jm} is NVL THEN *Xm* is NL.
- IF ΔV_j is PL and C_{jm} is PM THEN X_m is PS.
- IF ΔV_j is PM and C_{jm} is NS THEN X_m is NS.
- IF ΔV_j is PS and C_{jm} is NL THEN X_m is Z.

where X_m is the output of the m_{th} controller.

Transformation From Suggested Actions to Crisp Control Actions

The controllers are given priorities according to their controlling ability towards the critical load buses. These will affect the final settings of the controllers. As it can be observed from Table 2 that if a controller is having highest sensitivity towards a load bus where voltage deviation is very large then FLA will suggest 3 steps change (PL or NL). But if a controller is having no significant influence on critical

Table 2. Fuzzy inference matrix or fuzzy rules

ΔV_j	C_{jm}								
	NVL	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**	**PVL**
NVL	PL	PL	PM	PS	Z	NS	NM	NL	NL
NL	PM	PM	PS	PS	Z	NS	NS	NM	NM
NM	PM	PS	PS	PS	Z	NS	NS	NS	NM
NS	PS	Z	Z	Z	Z	Z	Z	Z	NS
Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
PS	NS	Z	Z	Z	Z	Z	Z	Z	PS
PM	NM	NS	NS	NS	Z	PS	PS	PS	PM
PL	NM	NM	NS	NS	Z	PS	PS	PM	PM

Table 3. Transformation of fuzzy output

Output Parameter	Implication
PL	3 positive steps
PM	2 positive steps
PS	1 positive step
Z	No change
NS	1 negative step
NM	2 negative steps
NL	3 negative steps

buses, then FLA will suggest Z. If the control action suggested by the FLA is Z, then no change is made in the controller setting. Thus, only significant controllers are changed to improve the voltage profile. In this way only few controllers of high sensitivity are used to achieve the desired objectives so that the reduction in complexity of the problem is ensured and also the voltage control operation is fast.

For an illustrative purpose, let us consider a sample system with three generators G1, G2 and G3, five OLTC transformers T1, T2,. . .T5, and four SVCs S1, S2,. . . S4. Totally, there are 12 controllers. Let us consider that five load buses L1, L2,. . . L5 are violating the voltage limit. For each of the critical load buses, a set of generator, OLTC, SVC controllers having highest sensitivity is obtained and a sample of that is given in Table 4.

It can be seen from Table 4 that generator G2, OLTC transformers T2, T4 and T5, and SVCs S2 and S4 are not in the list of most sensitive controllers for the critical load buses. Each column of controlling ability of the controllers [*C*] matrix corresponds to one controller. The sensitivity values for the generators and SVCs are either positive or negative, which depends on the system operating conditions. The controller movement direction (steps) should be positive to improve the voltage. For a particular controller, the proposed fuzzy logic approach may suggest different control actions (steps).

For peak load condition in the sample system, generator G1 is the highest sensitive controller for load buses L1 and L2. Let the control action (steps) for G1 suggested by FLA be THREE positive steps for L1 and TWO positive steps for L2. In that case, the highest step (setting) is selected to decide the final control setting for that generator (controller) using the MAX operation. On the contrary, if the control action (steps) suggested by FLA is negative, MIN operation is used to determine the final control setting for the generator. Similarly, the final control settings for the SVCs are also generated.

Table 4. Most sensitive controllers for sample system

Load Bus	Generator	OLTC	SVC
	(G1,. . . G3)	(T1,. . . T5)	(S1,. . . S4)
L1	G1	T1	S1
L2	G1	T1	S3
L3	G3	T3	S3
L4	G3	T1	S3
L5	G3	T3	S1

However, the sensitivity value for OLTC transformers can be both negative as well as positive. In order to determine the correct controller movement direction (steps) for overall improvement in system voltage profile, the algebraic sum of the elements of the voltage deviation sensitivity matrix $[H]$ (3) corresponding to the controller (transformer under consideration) is observed. A positive sign indicates that the reduction (negative controller movement direction) in tap improves the voltage, and a negative sign suggests that increase (positive controller movement direction) in tap will improve the voltage. So, if the suggested control action (positive/negative steps) by FLA is matching with this sign, then the suggested correction is incorporated in the final control settings of those controllers, otherwise no correction is made.

COMPUTATIONAL ALGORITHM

The algorithmic steps for the proposed approach are given below:

Step 1: For a given network topology, generation schedule and load data, run the state estimation/load flow program to get the initial operating condition of the given system such as voltage profile, real and reactive power losses, etc.
Step 2: Check for voltage violations. If there is any violations go to Step 3, otherwise go to Step 13.
Step 3: Advance fuzzy iteration count.
Step 4: Compute the voltage deviation (ΔV) at each of the load buses using (11).
Step 5: Compute the sensitivity matrix $[S]$ relating the dependent and control variables using (10).
Step 6: Calculate voltage deviation sensitivity matrix $[H]$ for all controllers using (3).
Step 7: Using the margin of the controllers, compute the controlling ability of the controllers' matrix $[C]$ using (2).
Step 8: Design fuzzy logic approach as explained in the Subsection FLA.
Step 9: Feed the input parameters (voltage deviation (ΔV) and controlling ability of the controllers $[C]$) to fuzzy logic approach and produce fuzzy output.
Step 10: Transform fuzzy output to discrete controller settings using Table 3.
Step 11: Using the new control variable settings, again perform the load flow analysis.
Step 12: Check for voltage violations. If there is any violation go to Step 3. Otherwise, go to Step 13.
Step 13: Print the results and terminate the program.
Step 14: The above steps are repeated for different operating conditions in the system.

SYSTEM STUDIES AND DISCUSSIONS

The fixed speed wind generators are of conventional asynchronous machines, which do not have capability to control the voltage, but rather absorb large levels of reactive power during low voltage conditions. The studies in the literature show that the FSWGs have significant impact on the system voltage performance (Moger & Dhadbanjan, 2017; Divya & Rao, 2006). Since these units do show its contribution/impact on system voltage profile, the presence of FSWGs in the system is absolutely necessary while studying the steady state voltage stability of grid connected wind farms. The active power output of the wind generators are obtained directly from the power curve provided by the manufacturer. The reactive power output of the FSWG is computed by considering the power factor of 0.95 leading (inductive) as per the prevailing industry practice. However, the VSWGs can provide necessary voltage support because of its flexibility in control design. Therefore, the VSWGs can participate in reactive power optimization process.

The control variables are switchable VAr compensators, grid OLTC transformers, OLTC transformers at the point of the common coupling of wind farms, generator excitations, and reactive power output of the variable speed wind generators. For all studies, initially it is assumed that all control variables are to be at their nominal settings, that is, all OLTC transformers tap position and the excitation of all the generators at their nominal value (i.e., 1.0 per unit), and the reactive power output of SVCs and VSWGs are operated at nil.

A comparative analysis is carried out with conventional LP based optimization technique (Dhadbanjan & Yesuratnam, 2006) to highlight the effectiveness of the proposed approach. The detailed methodology of the LP based reactive power optimization technique is explained in Appendix.

297-Bus Equivalent Grid Connected Wind System

A 24-bus, 400 kV level equivalent system of Indian southern region power grid (SR 24-bus equivalent system) with wind integration is considered to test the proposed approach. The single-line diagram of the system is shown in Figure 5. The southern region power grid covers the electrical network of four south Indian states such as Karnataka, Andra Pradesh, Tamil Nadu and Kerala. The system data is taken from (Moger, 2016). The system comprises of four generators, 16 transmission lines which are of 400 kV level lines connecting the four south Indian states, and 12 transformers. The real and reactive loads are connected at eight locations. The shunt reactors are connected at few buses for transient over voltage protection. The system has an initial peak load of 2060 MW and 1040 MVAr.

Three practical wind farms (wind farms with different wind generator types, that is, FSWGs and VSWGs) are considered for the reactive power coordination in grid connected wind farms. The three wind farms are connected at buses 5, 6 and 8. In each wind farm, there are six groups and each group comprises of same type of wind generators either fixed speed wind generators or variable speed wind generators. Totally, there are 45 wind generators. With a pad mounted transformer at each wind generator and a collector system station, there are 91 buses in each wind farm. When wind farms are operated at rated power, the penetration of wind power in the system is around 10%.

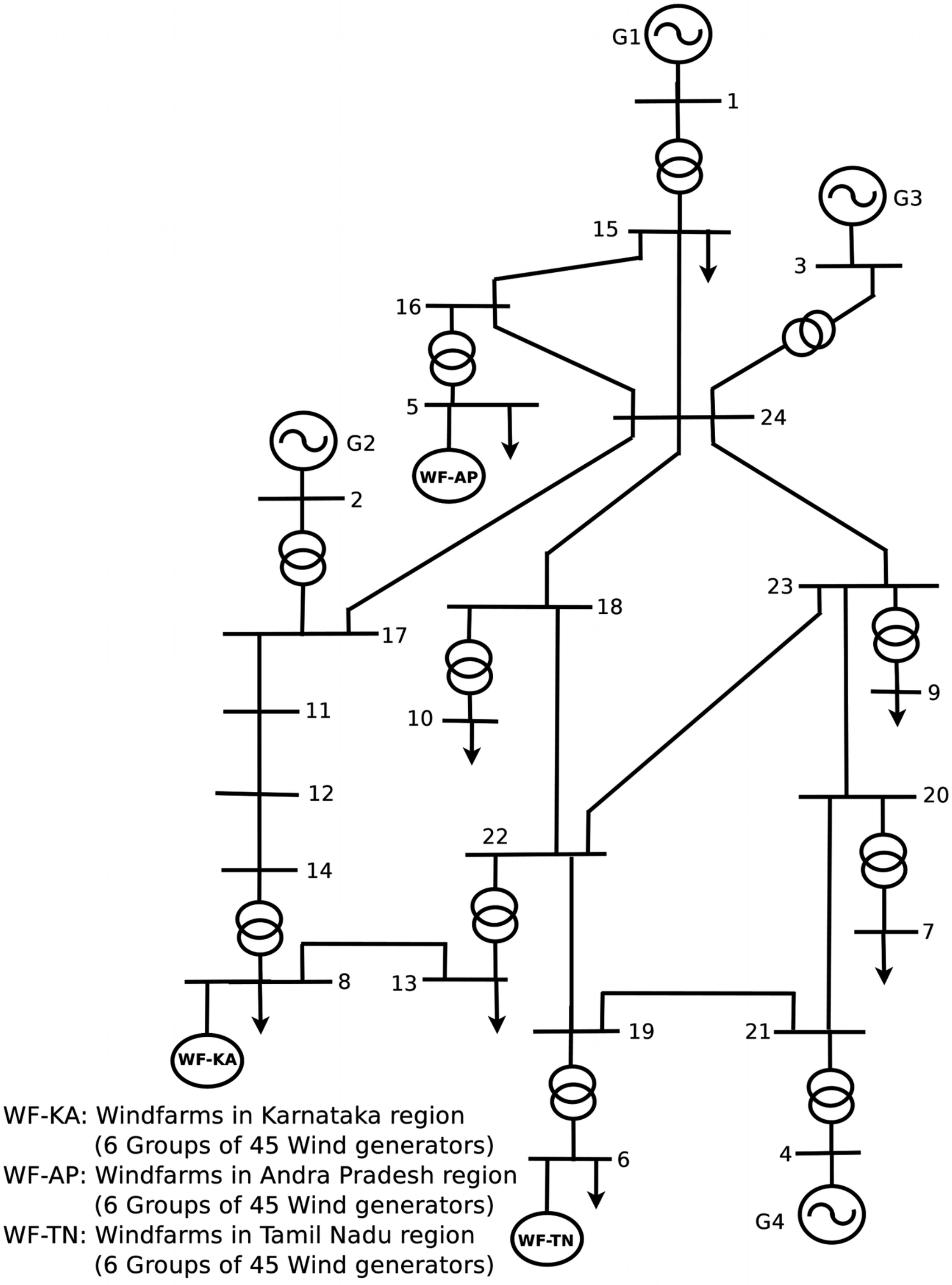
The fixed speed wind generators were predominantly employed during the early installations of wind generators. Presently, the variable speed wind generators become more popular because of advancements in the power electronics controller design. Due to the presence of mixed types of wind generators in the wind farms, the reactive power coordination or reactive power and voltage control analysis is carried out for two different ratios of wind generator units, that is, FSWGs to VSWGs in the wind farm.

The two different ratios of wind generators units considered for the studies are:

Scenario-1: Wind generator units ratio of 26:74 (FSWG:VSWG)
Scenario-2: Wind generator units ratio of 5:95 (FSWG:VSWG)

The topology structure for two different ratios of wind generator units (FSWG to VSWG) in the wind farms is the same. However, the wind generator units in the respective groups are replaced with the same power rating of different type of wind generator units to make it to a particular ratio. For each scenario, studies are carried out for two operating points/conditions in the system:

Figure 5. Single-line diagram of SR 24-bus equivalent system with wind farms



Case-1: Peak load condition.
Case-2: Single line outage/contingency.

As discussed in (Moger, 2016; Moger & Dhadbanjan, 2015), the line connected between the buses 24 and 23 is considered as one of the most severe contingency. This line is considered for the reactive power and voltage control analysis in the system.

For each operating point/condition, the system is evaluated with various performance indices or parameters, viz., system power loss (real and reactive power losses) and load bus voltage profile parameters (V_{min}, V_{max}, STDEV(V), $\sum(V^d - V^a)^2$ i.e., sum of the square of the voltage deviation from desired voltage of the buses, and voltage stability index at load buses (*L-index*)) to assess the effectiveness of the proposed approach.

Scenario-1: Wind Generator Units' Ratio of 26:74 (FSWG:VSWG)

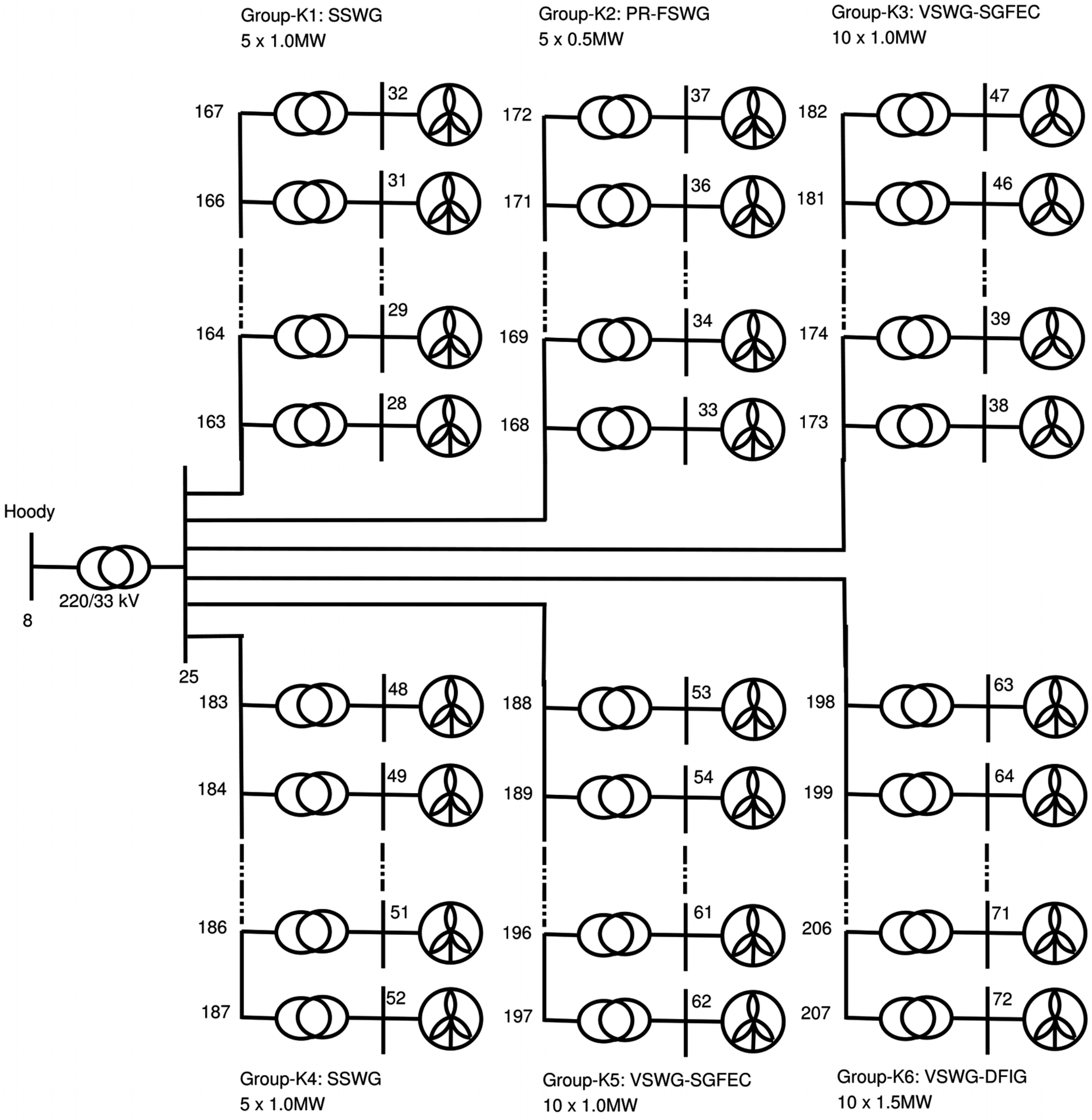
In this scenario, Group-1 consists of five semi-variable speed wind generators (SSWGs) and each rated for 1.0 MW. Group-2 consists of five pitch regulated fixed speed wind generators (PR-FSWGs) and each rated for 0.5 MW. Group-3 consists of 10 VSWG-DFIGs and each rated for 1.0 MW. Group-4 consists of five SSWGs and each rated for 1.0 MW. Group-5 consists of 10 VSWG-SGFECs and each rated for 1.0 MW. Group-6 consists of 10 VSWG-DFIGs and each rated for 1.5 MW. In total, there are 45 wind generators out of that 15 are FSWGs, which supply the power of 12.5 MW. Out of the total wind power, there is about 26% of wind power supplied by the FSWGs (which always consume reactive power) and these units do not participate in the reactive power optimization process. The configuration of individual wind farms for wind generator units ratio of 26:74 (FSWG:VSWG) is shown Figures 6, 7 and 8.

Case-1: System Under Peak Load Condition

The reactive power or voltage control analysis is carried out for peak load condition in the system. The system performance parameters and voltage/reactive power controllers setting from the proposed approach and other existing technique (Dhadbanjan & Yesuratnam, 2006) are given in Tables 5 and 6, respectively. It can be seen from Table 5 that under peak load condition the minimum voltage of the system improves from 0.856 p.u. to 0.9654 p.u. using the proposed approach and to 0.9599 p.u. using the conventional LP based optimization technique. Similarly, the voltage stability index (*L-index*) is also improved from 0.5083 to 0.3940 using the proposed approach whereas it reduces to 0.3926 using the conventional LP based optimization technique.

In addition, the conventional LP based optimization technique reduces the real power loss of the system to 35.82 MW whereas proposed approach reduces it to 36.77 MW. The standard deviation (STDEV) of the load voltage is used to quantify the amount of variation or dispersion of a set of load voltages. The STDEV value of the load voltages also improved to 0.0157 using the proposed approach and to 0.0162 using the conventional LP based optimization technique. The improvement in system voltage profile and voltage stability index (*L-index*) at the load buses from both these techniques are shown in Figures 9 and 10, respectively.

Figure 6. Single-line diagram of wind farm at Karnataka: WGUs ratio of 26:74 (FSWG:VSWG)



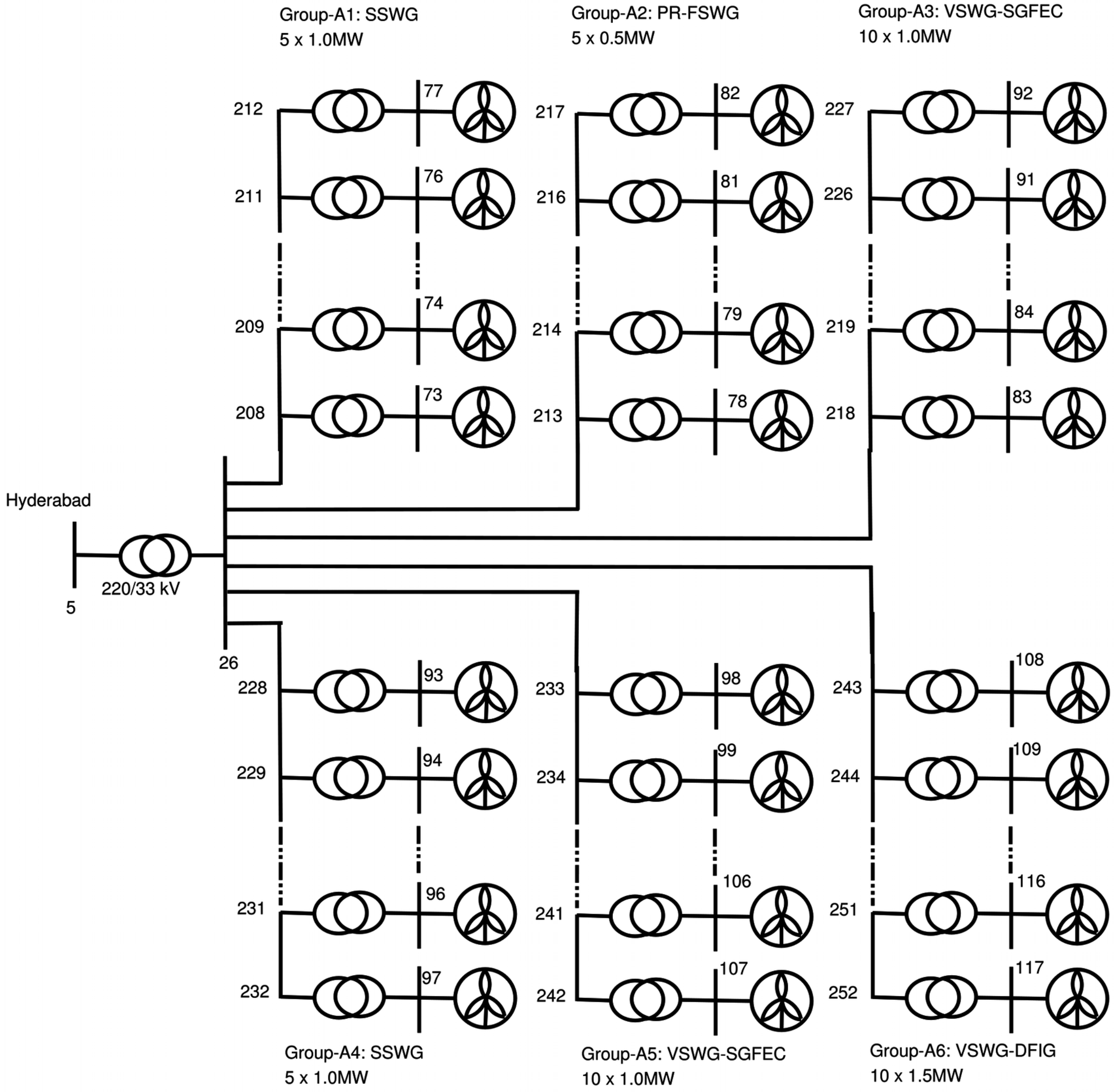
PR-FSWG: Pitch regulated-Fixed speed wind generating unit (0.5MW, 0.69kV)

VSWG-DFIG: Variable speed wind generating unit-DFIG (1.5MW, 0.69kV)

SSWG: Semi-variable speed wind generating unit (1.0MW, 0.69kV)

VSWG-SGFEC: Variable speed wind generating unit-Synchronous generator with front end converter (1.0MW, 0.69kV)

Figure 7. Single-line diagram of wind farm at Andra Pradesh: WGUs ratio of 26:74 (FSWG:VSWG)



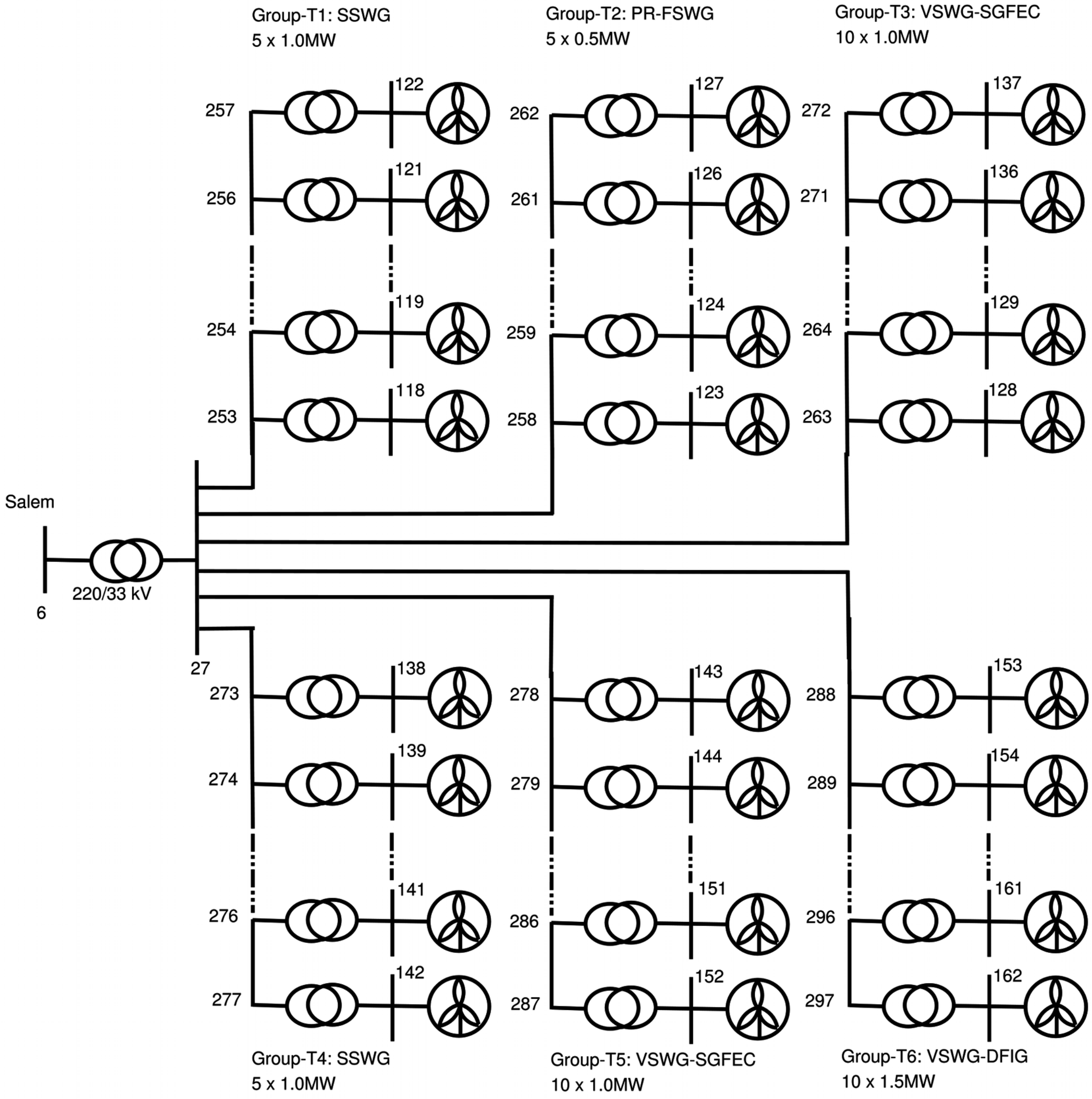
PR-FSWG: Pitch regulated-Fixed speed wind generating unit (0.5MW, 0.69kV)

VSWG-DFIG: Variable speed wind generating unit-DFIG (1.5MW, 0.69kV)

SSWG: Semi-variable speed wind generating unit (1.0MW, 0.69kV)

VSWG-SGFEC: Variable speed wind generating unit-Synchronous generator with front end converter (1.0MW, 0.69kV)

Figure 8. Single-line diagram of wind farm at Tamil Nadu: WGUs ratio of 26:74 (FSWG:VSWG)



PR-FSWG: Pitch regulated-Fixed speed wind generating unit (0.5MW, 0.69kV)

VSWG-DFIG: Variable speed wind generating unit-DFIG (1.5MW, 0.69kV)

SSWG: Semi-variable speed wind generating unit (1.0MW, 0.69kV)

VSWG-SGFEC: Variable speed wind generating unit-Synchronous generator with front end converter (1.0MW, 0.69kV)

Table 5. System performance parameters of 297-bus equivalent grid connected wind system under different operating points/conditions: WGUs ratio of 26:74 (FSWG:VSWG)

Parameters	Case-1: Peak Load			Case-2: Outage		
	Initial	FLA	LP	Initial	FLA	LP
$P_{loss}(MW)$	46.25	36.77	35.82	38.46	28.9	28.2
$Q_{loss}(MVAr)$	674.86	503.9	487.58	518.99	362.38	348.82
$V_{max}(p.u.)$	1.0001	1.041	1.0476	0.9985	1.0255	1.0319
$V_{min}(p.u.)$	0.856	0.9654	0.9599	0.8573	0.9554	0.9514
STDEV(V)	0.0269	0.0157	0.0162	0.0257	0.0145	0.0159
$\sum(V^d - V^a)^2$	2.5076	0.0456	0.0992	1.9352	0.0337	0.1
L^{max}-*index*	0.5083	0.394	0.3926	0.4475	0.3458	0.3347

The number of controllers used during the first two iterations of the proposed fuzzy logic approach is given in Table 7. It can be seen from Table 7 that the proposed approach used 106 controllers during the first iteration and only 15 controllers during the second iteration. The number of controllers in subsequent iterations is further reduced.

Inference

It can be observed from the simulation results that the system performance produced by the proposed approach is closely in agreement with that produced from the conventional LP based reactive power optimization technique. During each iteration, the proposed fuzzy logic approach uses only few reactive power/voltage controllers of high sensitivity to achieve the desired objectives. Since the number of controllers in each iteration is reduced, the computational time for each iteration is also reduced. Hence, the overall computational effort is reduced.

Case-2: System Under Single Line Contingency Case

Similar to the analysis on peak load condition, the reactive power or voltage control analysis is carried out for single line contingency case. The system performance parameters and voltage/reactive power controllers setting from the proposed approach and other existing technique (Dhadbanjan & Yesuratnam, 2006) are also given in Tables 5 and 6, respectively. It can be seen from Table 5 that under single line contingency case the minimum voltage of the system improves from 0.8573 p.u. to 0.9554 p.u. using the proposed approach and to 0.9514 p.u. using the conventional LP based optimization technique. Similarly, the voltage stability index (*L-index*) is also improved from 0.4475 to 0.3458 using the proposed approach whereas it reduces to 0.3347 using the conventional LP based optimization technique.

In addition, the conventional LP based optimization technique reduces the real power loss of the system to 28.20 MW whereas proposed approach reduces it to 28.90 MW. Similarly, the STDEV value of the load voltages also improved to 0.0145 using the proposed approach and to 0.0159 using the conventional LP based optimization technique. The improvement in system voltage profile and voltage stability index (*L-index*) at the load buses from both these techniques are shown in Figures 11 and 12, respectively.

Table 6. Controllers settings of 297-bus equivalent grid connected wind system under different operating points/conditions: WGUs ratio of 26:74 (FSWG:VSWG)

Transformer (OLTC) Tap Settings						
Fbus-Tbus	**Case-1: Peak Load**			**Case-2: Outage**		
	Initial	**FLA**	**LP**	**Initial**	**FLA**	**LP**
16-5	1	0.9625	0.95	1	0.975	0.9875
19-6	1	0.975	0.975	1	0.9875	1.0125
20-7	1	0.9625	0.9625	1	0.9625	0.9625
14-8	1	1	0.95	1	1	0.95
23-9	1	0.9875	1	1	0.9625	0.975
18-10	1	0.9875	1	1	0.9875	1
22-13	1	0.9625	0.9875	1	0.975	1
8-25	1	0.975	1.025	1	0.975	1.025
5-26	1	0.975	1	1	0.975	1.0125
6-27	1	0.9875	1	1	0.9875	1.0125
Voltage Settings of the Generator Excitation (p.u.)						
Gen. Bus	**Case-1: Peak Load**			**Case-2: Outage**		
	Initial	**FLA**	**LP**	**Initial**	**FLA**	**LP**
1	1	1.05	1.05	1	1.025	1.025
2	1	1	1.025	1	1	1.025
3	1	1.0125	1.05	1	1	1.025
4	1	1.05	1.05	1	1.05	1.05
Reactive Power Output of SVCs (MVAr)						
SVC Bus	**Case-1: Peak Load**			**Case-2: Outage**		
	Initial	**FLA**	**LP**	**Initial**	**FLA**	**LP**
5	0	6	8	0	2	6
6	0	2	8	0	2	6
7	0	4	8	0	6	8
8	0	6	6	0	8	8
Total Reactive Power Output of VSWGs in the Wind Farms (MVAr)						
Wind Farms	**Case-1: Peak Load**			**Case-2: Outage**		
	Initial	**FLA**	**LP**	**Initial**	**FLA**	**LP**
WF-KAR	0	5.3	7	0	3.8	7
WF-AP	0	5.3	7	0	3.5	7
WF-TN	0	3.5	7	0	2	7

Table 7. Number of controllers used in fuzzy iterations

Total Number of Controllers = 108	
1st Iteration	**2nd Iteration**
106	15

Figure 9. Voltage profile of SR 24-bus equivalent system with wind integration ratio of 26:74 (FSWG:VSWG) under peak load condition

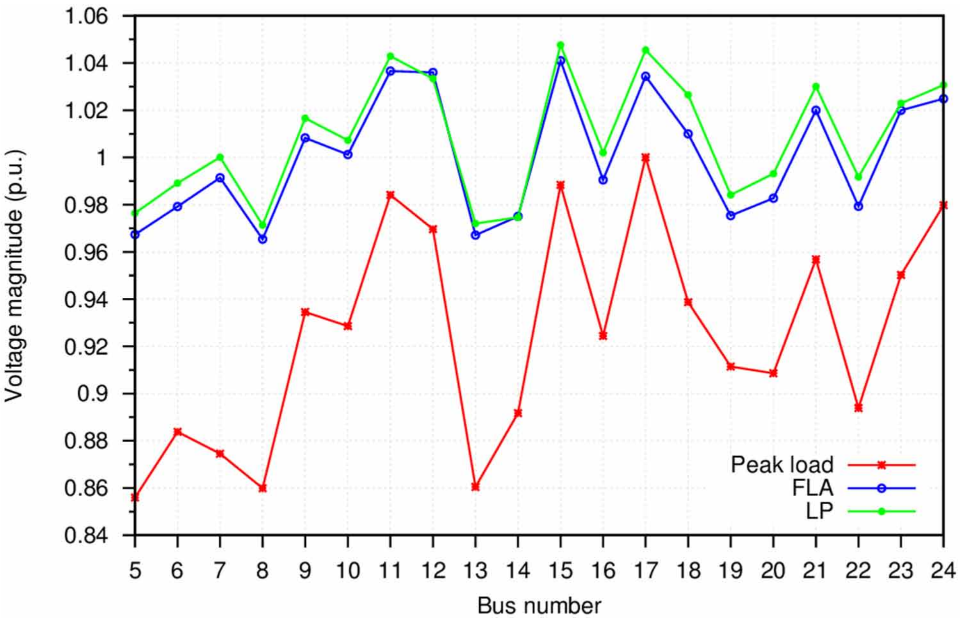


Figure 10. Voltage stability index (L-index) of SR 24-bus equivalent system with wind integration ratio of 26:74 (FSWG:VSWG) under peak load condition

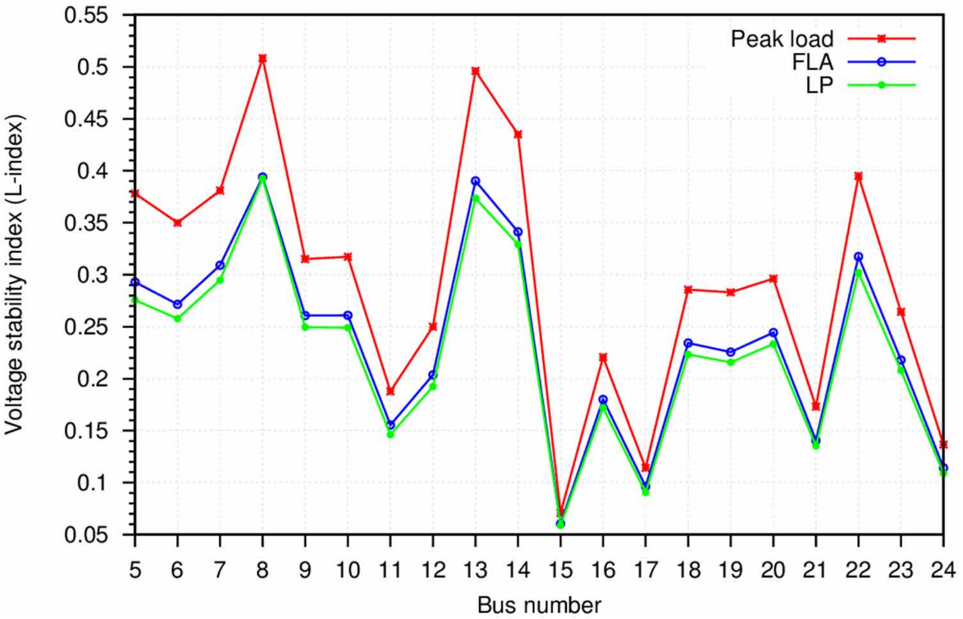


Figure 11. Voltage profile of SR 24-bus equivalent system with wind integration ratio of 26:74 (FSWG:VSWG) under outage/contingency condition

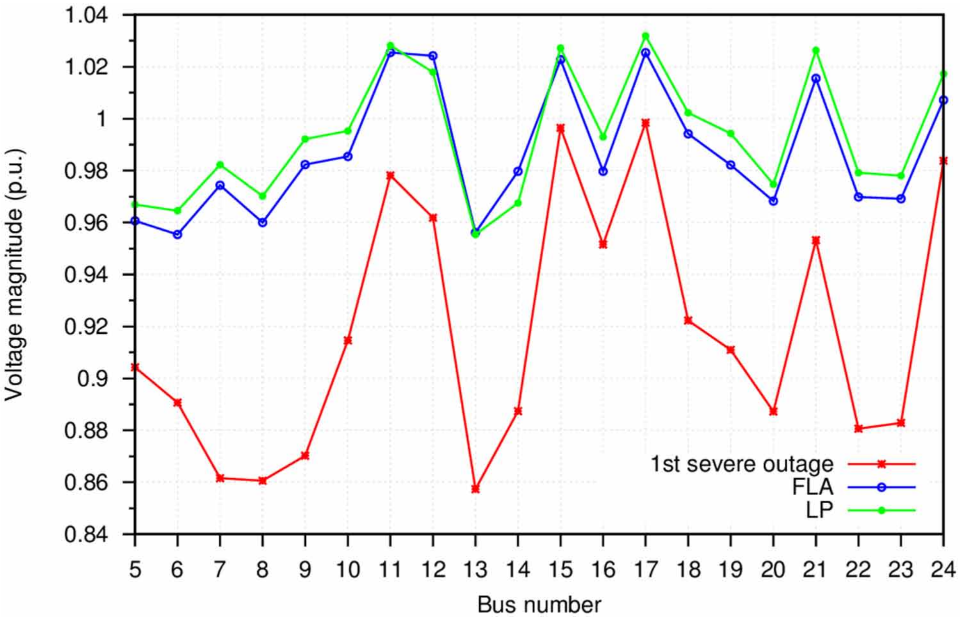
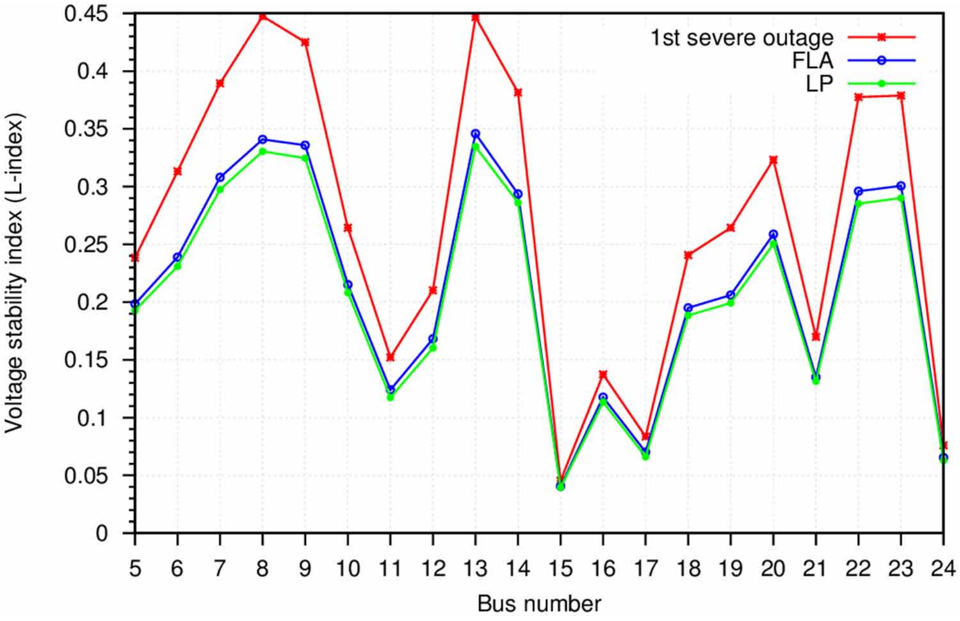


Figure 12. Voltage stability index (L-index) of SR 24-bus equivalent system with wind integration ratio of 26:74 (FSWG:VSWG) under outage/contingency condition



Scenario-2: Wind Generator Units' Ratio of 5:95 (FSWG:VSWG)

In this scenario, Group-1 consists of five VSWG-SGFECs and each rated for 1.0 MW. Group-2 consists of five pitch regulated fixed speed wind generators (PR-FSWGs) and each rated for 0.5 MW. Group-3 consists of 10 VSWG-SGFECs and each rated for 1.0 MW. Group-4 consists of five VSWG-SGFECs and each rated for 1.0 MW. Group-5 consists of 10 VSWG-SGFECs and each rated for 1.0 MW. Group-6 consists of 10 VSWG-DFIGs and each rated for 1.5 MW. In total, there are 45 wind generators out of that 5 are FSWGs, which supply the power of 2.5 MW. Out of the total wind power, there is about 5% of wind power supplied by the FSWGs (which always consume reactive power) and these units do not participate in the reactive power optimization process. The configurations of individual wind farms for wind generator units ratio of 5:95 (FSWG:VSWG) is shown in Figures 13, 14 and 15.

Similar to scenario-1, the reactive power or voltage control analysis is carried out for both peak load as well as single line contingency case. The system performance parameters and voltage/reactive power controllers setting for both the cases (Dhadbanjan & Yesuratnam, 2006) are given in Tables 8 and 9, respectively.

In addition, the improvement in system voltage profile for each of the cases is shown in Figures 16 and 17. Similarly, voltage stability index (*L-index*) at each of the load buses is shown in Figures 18 and 19.

In this scenario also it can be observed from the simulation results that the system performance produced by the proposed approach is closely in agreement with that produced from the conventional LP based reactive power optimization technique.

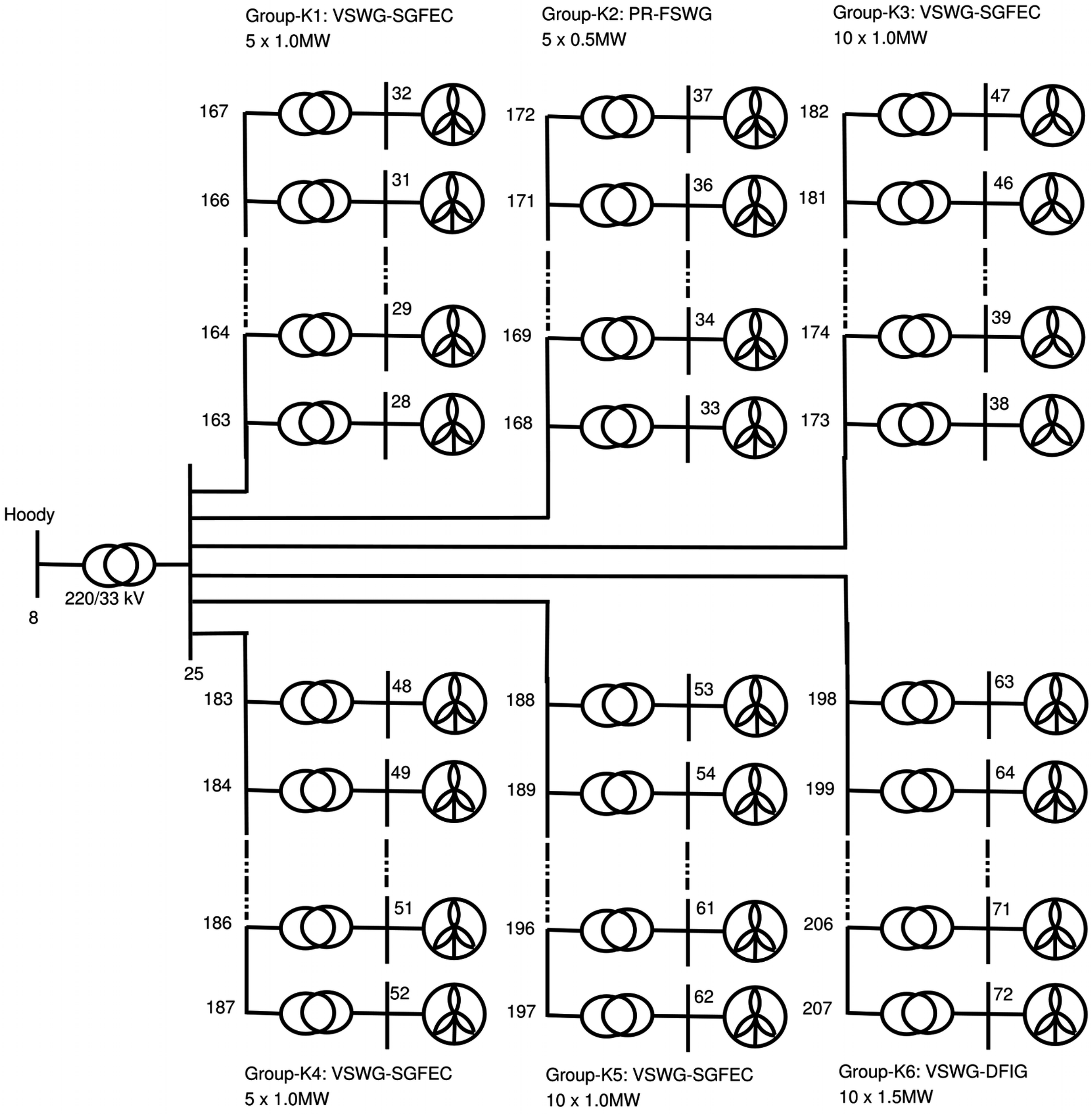
417-Bus Equivalent Grid Connected Wind System

The proposed approach is also tested on a 79-bus equivalent system with wind farms, which is a part of southern region power grid (SR 79-bus equivalent system). The single-line diagram of the system is shown in Figure 20. The southern region power grid covers the electrical network of four south Indian states such as Karnataka, Andra Pradesh, Tamil Nadu and Kerala.

The system data is taken from (Moger, 2016). The system is comprising of 10 conventional generators, 89 transmission lines which are of 400/200 kV level lines connecting Karnataka, Andra Pradesh, Tamil Nadu and Kerala states, and 12 transformers. The real and reactive loads are connected at 47 locations. The shunt reactors are connected at few buses for transient over voltage protection. The system has an initial peak load of 4113.5 MW and 1650.92 MVAr.

The system is connected with four practical wind farms (wind farms with different wind generator types, that is, FSWGs and VSWGs), which are connected at buses 36, 51, 43 and 71. Out of the total 164 wind generators, 56 units of PR-FSWG (FSWG) and each rated for 2.0 MW, 15 units of SGFEC (VSWG) and each rated for 2.0 MW, and 93 units of DFIG (VSWG) and each rated for 2.0 MW. Out of the total wind power, there is about 34% of wind power supplied by the FSWGs (which always consume reactive power) and these units do not participate in the reactive power optimization process. When wind farms are operated at rated power, the penetration of wind power in the system is around 10%. With a pad mounted transformer at each wind generator and the collector system stations, the total number of buses in all wind farms is 338. The configurations of individual wind farms are shown in Figures 21 and 22. Similar to 297-bus equivalent grid connected wind farm, system studies are carried out for two operating points/conditions in the system:

Figure 13. Single-line diagram of wind farm at Karnataka: WGUs ratio of 5:95 (FSWG:VSWG)

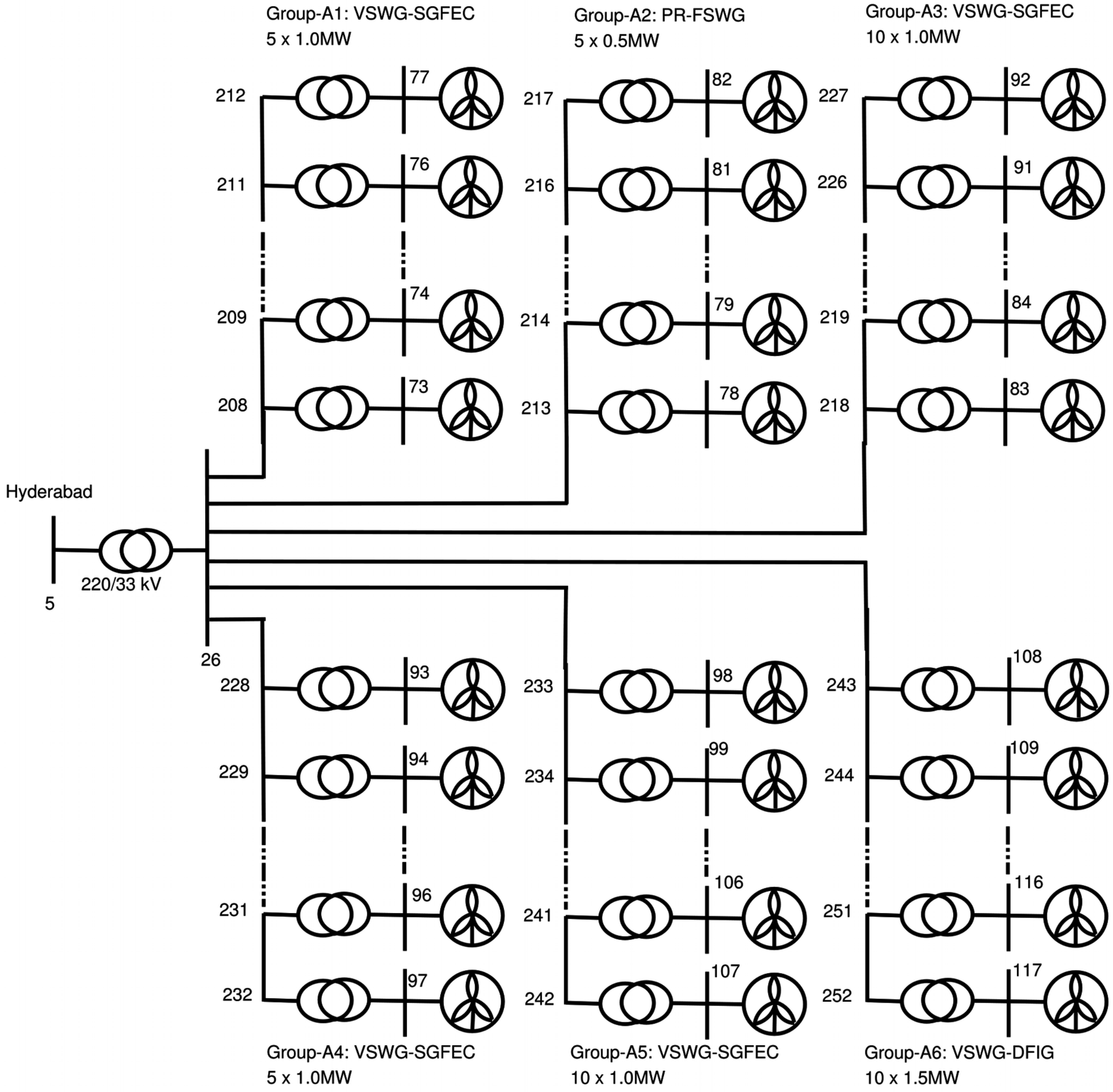


VSWG-DFIG: Variable speed wind generating unit-DFIG (1.5MW, 0.69kV)

PR-FSWG: Pitch regulated-Fixed speed wind generating unit (0.5MW, 0.69kV)

VSWG-SGFEC: Variable speed wind generating unit-Synchronous generator with front end converter (1.0MW, 0.69kV)

Figure 14. Single-line diagram of wind farm at Andra Pradesh: WGUs ratio of 5:95 (FSWG:VSWG)

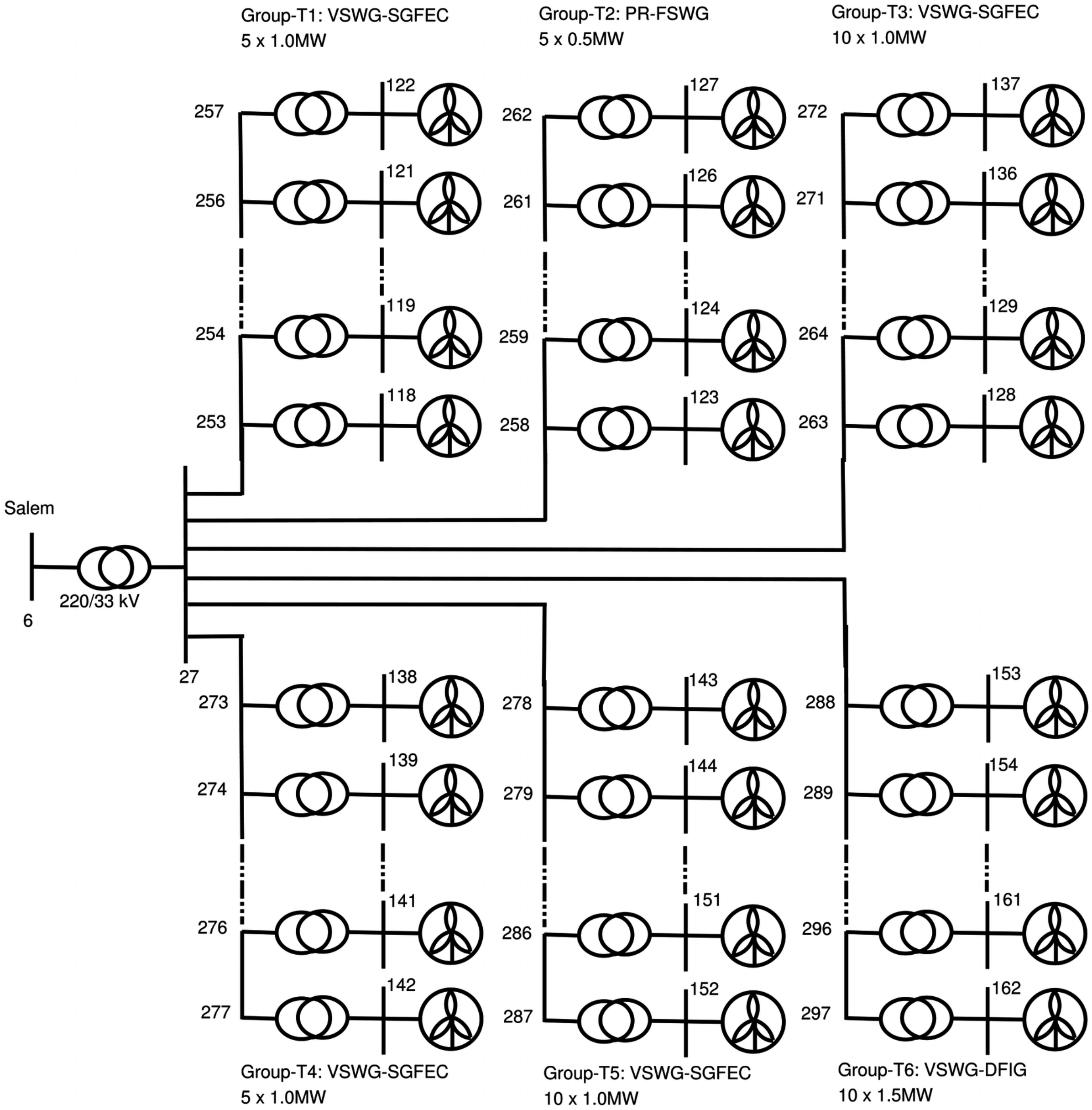


PR-FSWG: Pitch regulated-Fixed speed wind generating unit (0.5MW, 0.69kV)

VSWG-DFIG: Variable speed wind generating unit-DFIG (1.5MW, 0.69kV)

VSWG-SGFEC: Variable speed wind generating unit-Synchronous generator with front end converter (1.0MW, 0.69kV)

Figure 15. Single-line diagram of wind farm at Tamil Nadu: WGUs ratio of 5:95 (FSWG:VSWG)



PR-FSWG: Pitch regulated-Fixed speed wind generating unit (0.5MW, 0.69kV)

VSWG-SGFEC: Variable speed wind generating unit-Synchronous generator with front end converter (1.0MW, 0.69kV)

VSWG-DFIG: Variable speed wind generating unit-DFIG (1.5MW, 0.69kV)

Table 8. System performance parameters of 297-bus equivalent grid connected wind system under different operating points/conditions: WGUs ratio of 5:95 (FSWG:VSWG)

Parameters	Case-1: Peak Load			Case-2: Outage		
	Initial	FLA	LP	Initial	FLA	LP
$P_{loss}(MW)$	46.25	36.34	36.6	38.46	28.35	27.8
$Q_{loss}(MVAr)$	674.86	499.07	497.38	518.99	355.7	344.23
$V_{max}(p.u.)$	1.0001	1.0349	1.0333	0.9985	1.0328	1.0427
$V_{min}(p.u.)$	0.856	0.9593	0.9511	0.8573	0.9621	0.9536
STDEV(V)	0.0269	0.015	0.0156	0.0257	0.0145	0.0157
$\sum(V^d - V^a)^2$	2.5076	0.059	0.0931	1.9352	0.0408	0.0986
L^{max}*-index*	0.5083	0.3913	0.3895	0.4475	0.3394	0.331

Case-1: Peak load condition.
Case-2: Single line outage/contingency.

As discussed in (Moger, 2016; Moger & Dhadbanjan, 2015), the line connected between the buses 20 and 23 is considered as one of the most severe contingency. This line is considered for the reactive power and voltage control analysis in the system.

For each operating point/condition, the system is evaluated with various performance indices or parameters to assess the effectiveness of the proposed approach.

Case-1: System Under Peak Load Condition

The reactive power or voltage control analysis is carried out for peak load condition in the system. The system performance parameters and voltage/reactive power controllers setting from the proposed approach and other existing technique (Dhadbanjan & Yesuratnam, 2006) are given in Tables 10 and 11, respectively. It can be seen from Table 10 that under peak load condition the minimum voltage of the system improves from 0.8377 p.u. to 0.9585 p.u. using the proposed approach and to 0.9508 p.u. using the conventional LP based optimization technique. Similarly, the voltage stability index (*L-index*) is also improved from 0.6973 to 0.5142 using the proposed approach whereas it reduces to 0.528 using the conventional LP based optimization technique.

In addition, the conventional LP based optimization technique reduces the real power loss of the system to 163.70 MW whereas proposed approach reduces it to 163.32 MW. Similarly, the STDEV value of the load voltages also improved to 0.0185 using the proposed approach and to 0.0188 using the conventional LP based optimization technique. The improvement in system voltage profile and voltage stability index (*L-index*) at the load buses using both these techniques are shown in Figures 23 and 24, respectively.

Case-2: System Under Single Line Contingency Case

Similar to the analysis on peak load condition, the reactive power or voltage control analysis is carried out for single line contingency case. The system performance parameters and voltage/reactive power controllers setting using the proposed approach and other existing technique (Dhadbanjan & Yesuratnam,

Table 9. Controllers settings of 297-bus equivalent grid connected wind system under different operating points/conditions: WGUs ratio of 5:95 (FSWG:VSWG)

Transformer (OLTC) Tap Settings

Fbus-Tbus	Case-1: Peak Load			Case-2: Outage		
	Initial	FLA	LP	Initial	FLA	LP
16-5	1	0.9625	0.95	1	0.975	0.9875
19-6	1	0.975	1	1	0.9875	1.0125
20-7	1	0.9625	0.9625	1	0.9625	0.9625
14-8	1	1	0.95	1	1	0.975
23-9	1	0.9875	1	1	0.9625	0.975
18-10	1	0.9875	1	1	0.9875	1
22-13	1	0.975	0.9875	1	0.975	1
8-25	1	0.975	1.025	1	0.9875	1.025
5-26	1	0.975	1.025	1	0.975	1.025
6-27	1	0.9875	1.025	1	0.9875	1.025

Voltage Settings of the Generator Excitation (p.u.)

Gen. Bus	Case-1: Peak Load			Case-2: Outage		
	Initial	FLA	LP	Initial	FLA	LP
1	1	1.05	1.025	1	1.025	1.025
2	1	1	1.0125	1	1	1.025
3	1	1.0125	1.025	1	1	1.025
4	1	1.05	1.05	1	1.05	1.05

Reactive Power Output of SVCs (MVAr)

SVC Bus	Case-1: Peak Load			Case-2: Outage		
	Initial	FLA	LP	Initial	FLA	LP
5	0	6	6	0	4	6
6	0	4	8	0	2	6
7	0	4	8	0	8	8
8	0	8	8	0	10	6

Total Reactive Power Output of VSWGs in the Wind Farms (MVAr)

Wind Farms	Case-1: Peak Load			Case-2: Outage		
	Initial	FLA	LP	Initial	FLA	LP
WF-KAR	0	4.8	9	0	5.1	9
WF-AP	0	4.95	9	0	4.65	9.2
WF-TN	0	4.65	9	0	3	9

Figure 16. Voltage profile of SR 24-bus equivalent system with wind integration ratio of 5:95 (FSWG:VSWG) under peak load condition

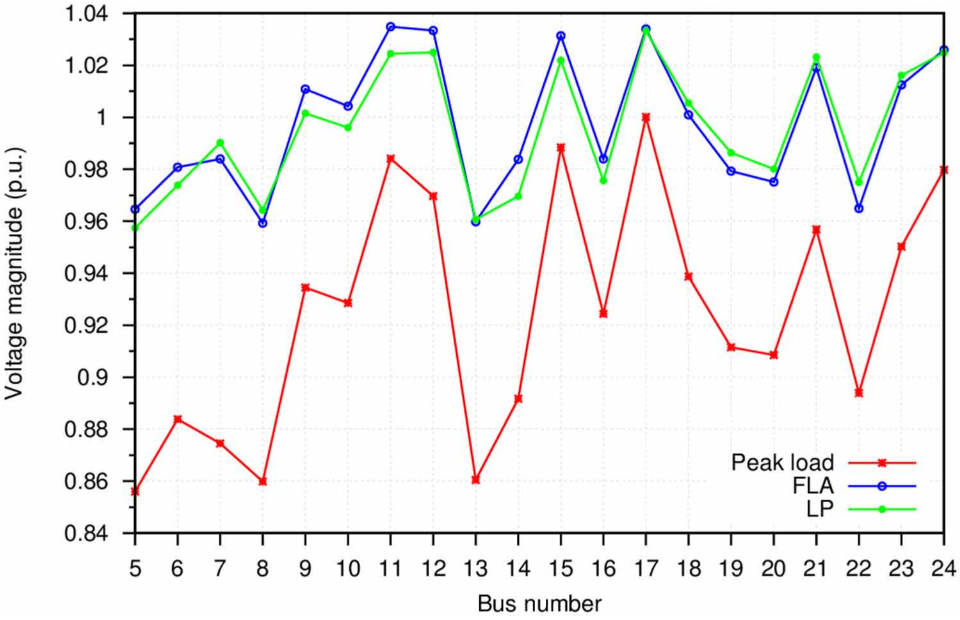


Figure 17. Voltage profile of SR 24-bus equivalent system with wind integration ratio of 5:95 (FSWG:VSWG) under outage/contingency condition

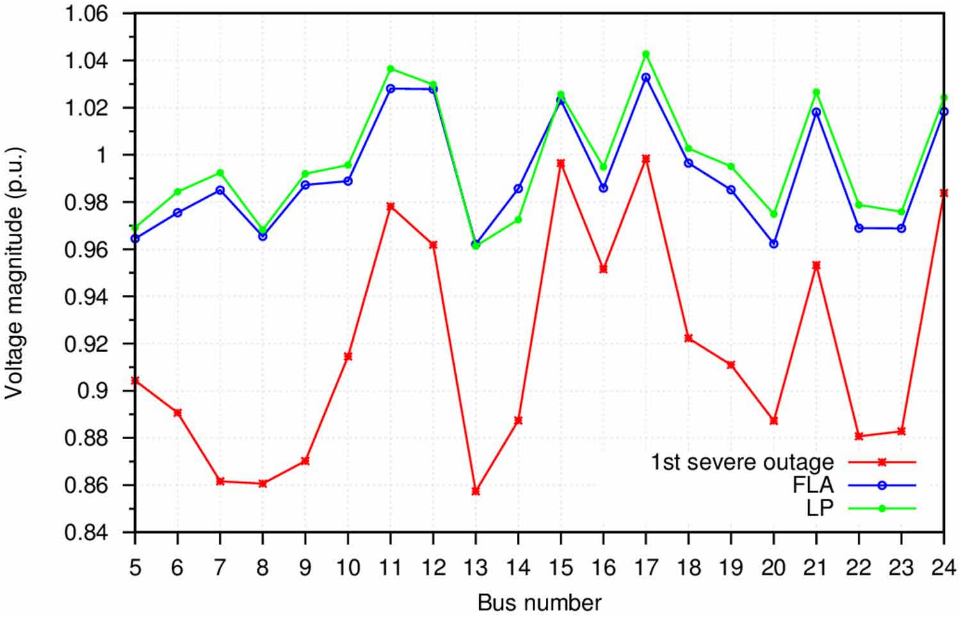


Figure 18. Voltage stability index (L-index) of SR 24-bus equivalent system with wind integration ratio of 5:95 (FSWG:VSWG) under peak load condition

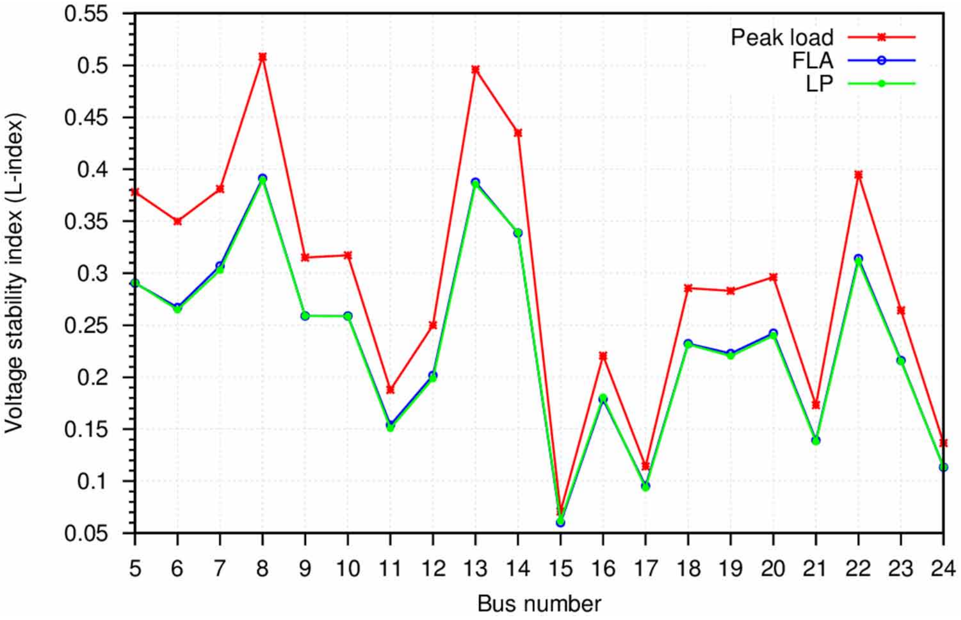


Figure 19. Voltage stability index (L-index) of SR 24-bus equivalent system with wind integration ratio of 5:95 (FSWG:VSWG) under outage/contingency condition

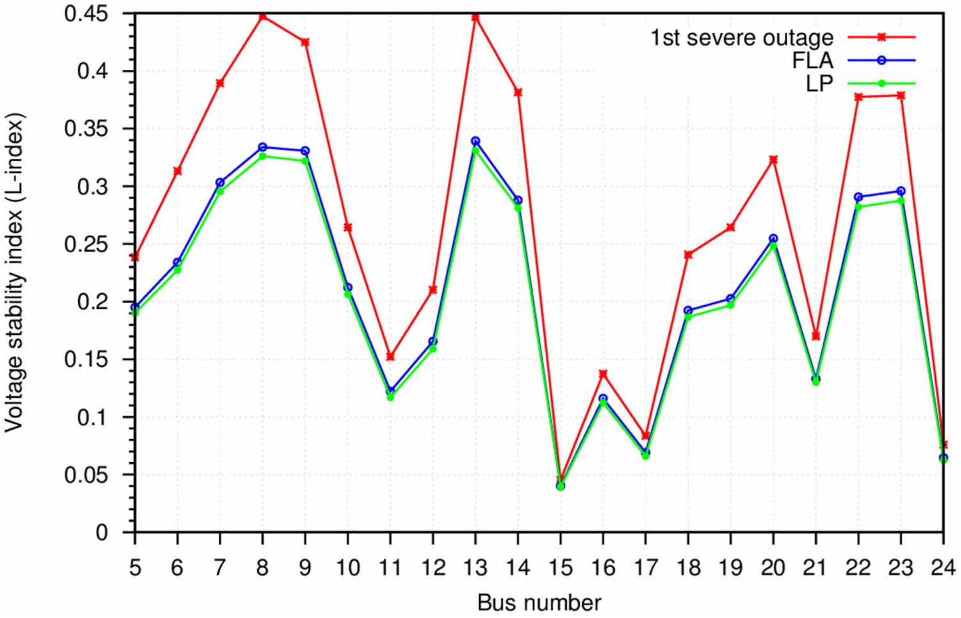


Figure 20. Single-line diagram of SR 79-bus equivalent system with wind farms

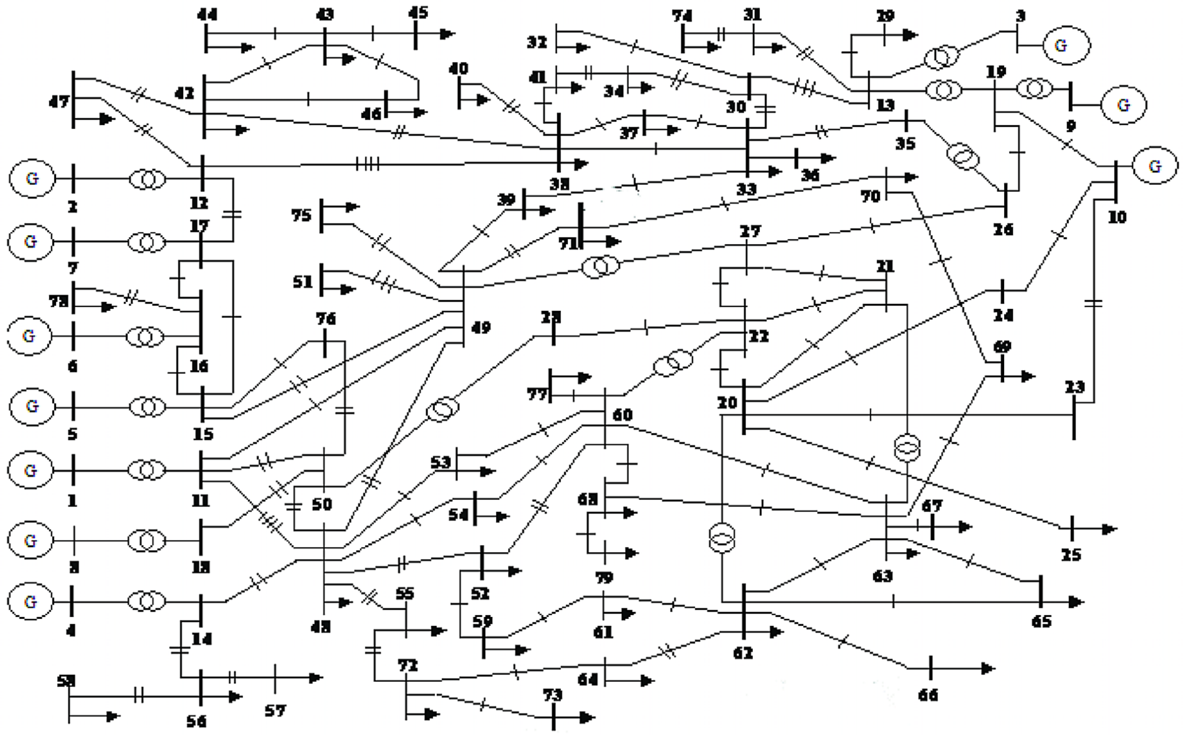


Figure 21. Single-line diagram of wind farm at Karnataka (Part-1)

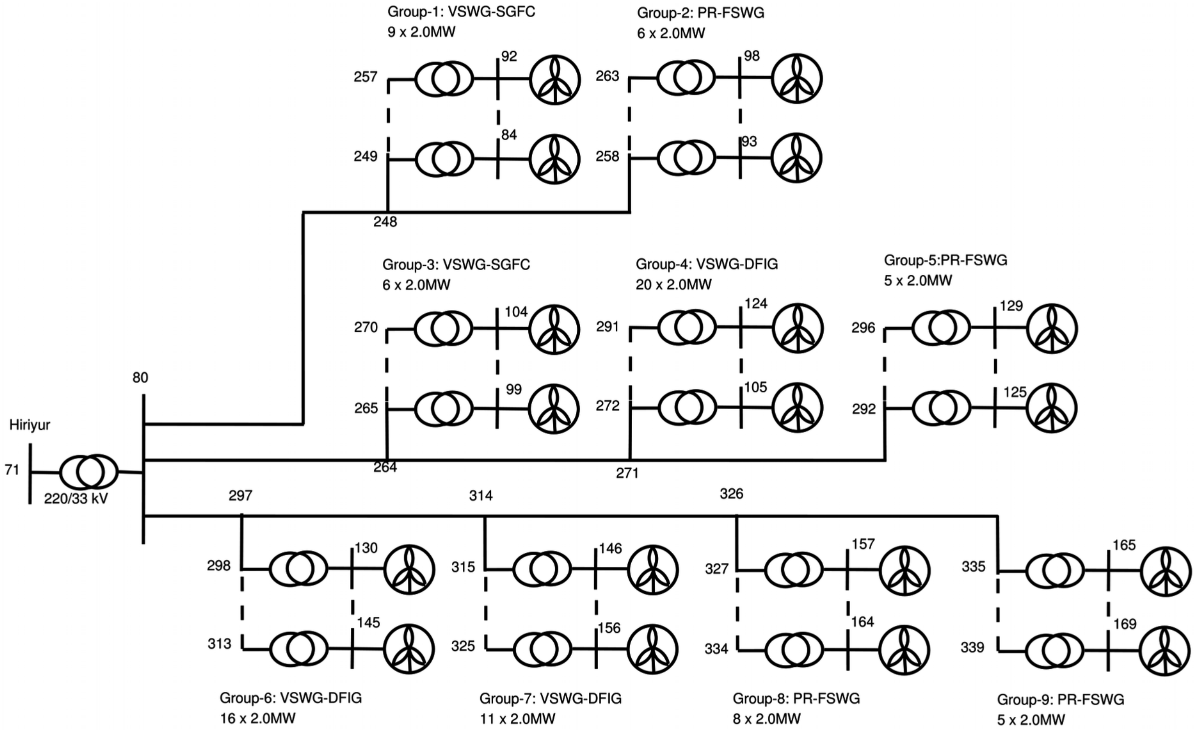


Figure 22. Single-line diagram of wind farm at Karnataka (Part-2)

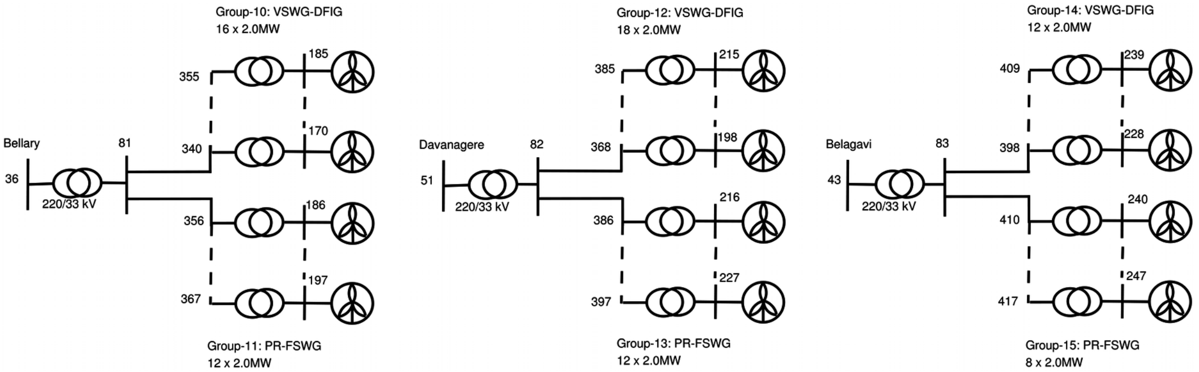


Table 10. System performance parameters of 417-bus equivalent grid connected wind system under different operating points/conditions

Parameters	Case-1: Peak Load			Case-2: Outage		
	Initial	FLA	LP	Initial	FLA	LP
$P_{loss}(MW)$	194.78	163.32	163.7	160.32	145.41	145.58
$Q_{loss}(MVAr)$	1549.85	1292.31	1282.69	1289.44	1148.33	1140.01
$V_{max}(p.u.)$	0.9823	1.0408	1.0381	0.988	1.037	1.0281
$V_{min}(p.u.)$	0.8377	0.9585	0.9508	0.8619	0.9621	0.9536
STDEV(V)	0.0266	0.0185	0.0188	0.0228	0.0172	0.0164
$\sum(V^d - V^a)^2$	1.923	0.1264	0.1868	1.1669	0.0808	0.1149
L^{max}-*index*	0.6973	0.5142	0.528	0.6684	0.5325	0.5327

2006) are also given in Tables 10 and 11, respectively. It can be seen from Table 10 that under single line contingency case the minimum voltage of the system improves from 0.8619 p.u. to 0.9621 p.u. using the proposed approach and to 0.9536 p.u. using the conventional LP based optimization technique. Similarly, the voltage stability index (*L-index*) is also improved from 0.6684 to 0.5325 using the proposed approach whereas it reduces to 0.5327 using the conventional LP based optimization technique.

In addition, the conventional LP based optimization technique reduces the system real power loss to 145.58 MW whereas proposed approach reduces it to 145.41 MW. Similarly, the STDEV value of the load voltages also improved to 0.0172 from proposed approach and to 0.0164 from the conventional LP based optimization technique. The improvement in system voltage profile and voltage stability index (*L-index*) at the load buses from both these techniques are shown in Figures 25 and 26, respectively.

Inference

Simulation results show that the system performance produced by the proposed approach is closely in agreement with that produced using the conventional LP based reactive power optimization technique. As observed in Table 7, the proposed fuzzy logic approach uses only few reactive power/voltage controllers

Table 11. Controllers settings of 417-bus equivalent grid connected wind system under different operating points/conditions

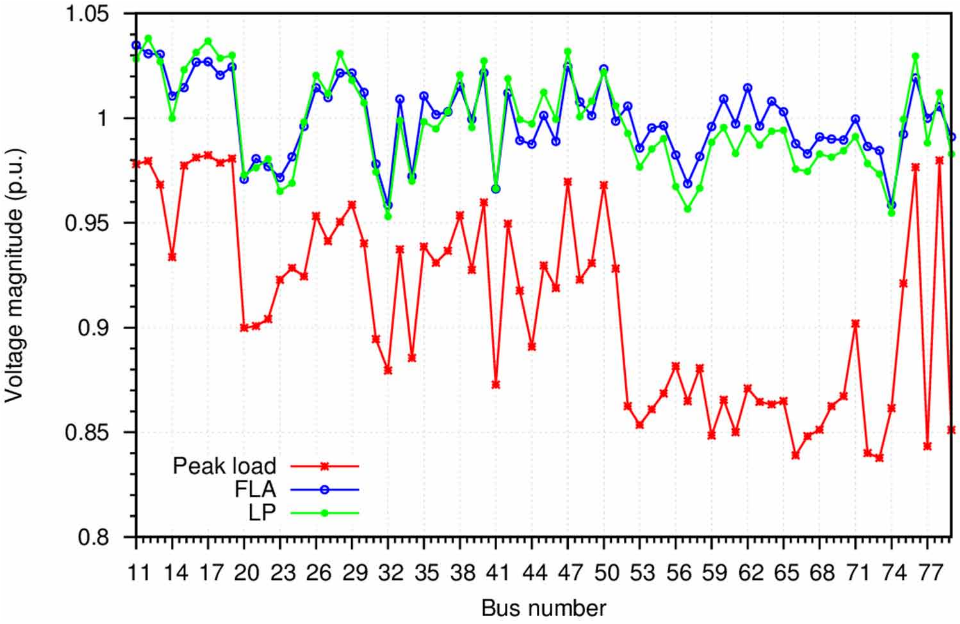
Transformer (OLTC) Tap Settings						
Fbus-Tbus	**Case-1: Peak Load**			**Case-2: Outage**		
	Initial	**FLA**	**LP**	**Initial**	**FLA**	**LP**
19-13	1	0.975	1	1	0.9875	0.975
26-35	1	0.975	1.025	1	0.9625	1
27-49	1	1.0125	0.9875	1	1	1.025
28-50	1	1.0125	1.025	1	1.025	1.025
22-60	1	0.925	0.9625	1	0.9625	1
20-62	1	0.925	0.9625	1	0.95	1
21-63	1	0.9875	0.9625	1	0.975	1
36-81	1	0.975	1.0375	1	0.9875	1.025
43-83	1	0.975	1.0375	1	0.9875	1.025
51-82	1	0.975	1.0375	1	0.9875	1.025
71-80	1	1.0125	1.0625	1	1	1.025
Voltage Settings of the Generator Excitation (p.u.)						
Gen. Bus	**Case-1: Peak Load**			**Case-2: Outage**		
	Initial	**FLA**	**LP**	**Initial**	**FLA**	**LP**
1	1	1.05	1.0375	1	1.0375	1.025
2	1	1.05	1.05	1	1.0375	1.025
3	1	1.05	1.05	1	1.05	1.025
4	1	1.0202	1.0077	1	1.0165	1.0165
5	1	1	1.0375	1	1	1.025
6	1	1	1.05	1	1	1.025
7	1	1	1.05	1	1	1.025
8	1	1	1.0375	1	1	1.025
9	1	1	1.05	1	1	1.025
10	1	1.028	1.003	1	1.025	1.025
Reactive Power Output of SVCs (MVAr)						
SVC Bus	**Case-1: Peak Load**			**Case-2: Outage**		
	Initial	**FLA**	**LP**	**Initial**	**FLA**	**LP**
41	0	25	25	0	15	15
44	0	15	25	0	10	15
57	0	30	25	0	10	15
59	0	15	20	0	15	15
70	0	15	20	0	5	15
72	0	25	20	0	15	15
74	0	25	25	0	20	15
77	0	25	20	0	15	15

continued on following page

Table 11. Continued

Total Reactive Power Output of VSWGs in the Wind Farms (MVAr)						
Wind Farms	**Case-1: Peak Load**			**Case-2: Outage**		
	Initial	**FLA**	**LP**	**Initial**	**FLA**	**LP**
WF at 71bus	0	21.8	20.783	0	14.4	15.0852
WF at 36bus	0	3.2	10.5184	0	3.2	6.4
WF at 51bus	0	3.6	8.2332	0	3.6	7.2
WF at 43bus	0	2.6	7.8888	0	2.6	4.8

Figure 23. Voltage profile of SR 79-bus equivalent system with wind integration under peak load condition



of high sensitivity to achieve the desired objectives so that the reduction in complexity of the problem is ensured and also the operation is fast.

FUTURE RESEARCH DIRECTIONS

The reactive power coordination in grid connected wind systems is carried out in accordance with the grid code compliance (Wu et al., 2010; Tsili & Papathanassiou, 2009). The mandatory requirement of power factor at the point of connection will restrict the full utilization of the reactive power capability of the variable speed wind generating units. However, the reactive power capability curve of the variable speed wind generators indicates that there is an additional supply of reactive power over the regulated power factor especially when the wind turbine operates below its rated power output. By utilizing the variable speed wind generators reactive power capability, the system operator will get more reactive

Figure 24. Voltage stability index (L-index) of SR 79-bus equivalent system with wind integration under peak load condition

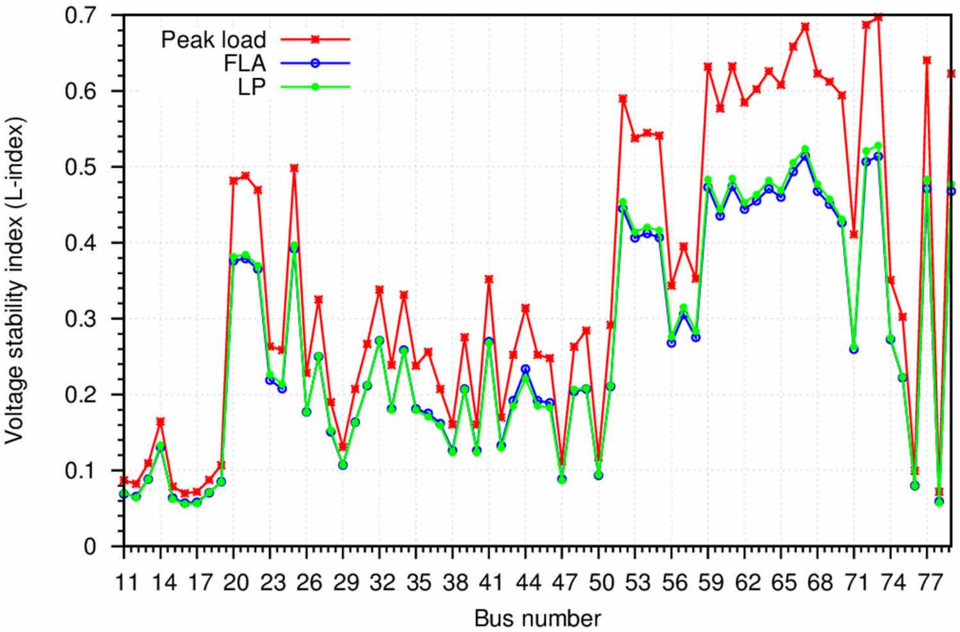


Figure 25. Voltage profile of SR 79-bus equivalent system with wind integration under outage/contingency condition

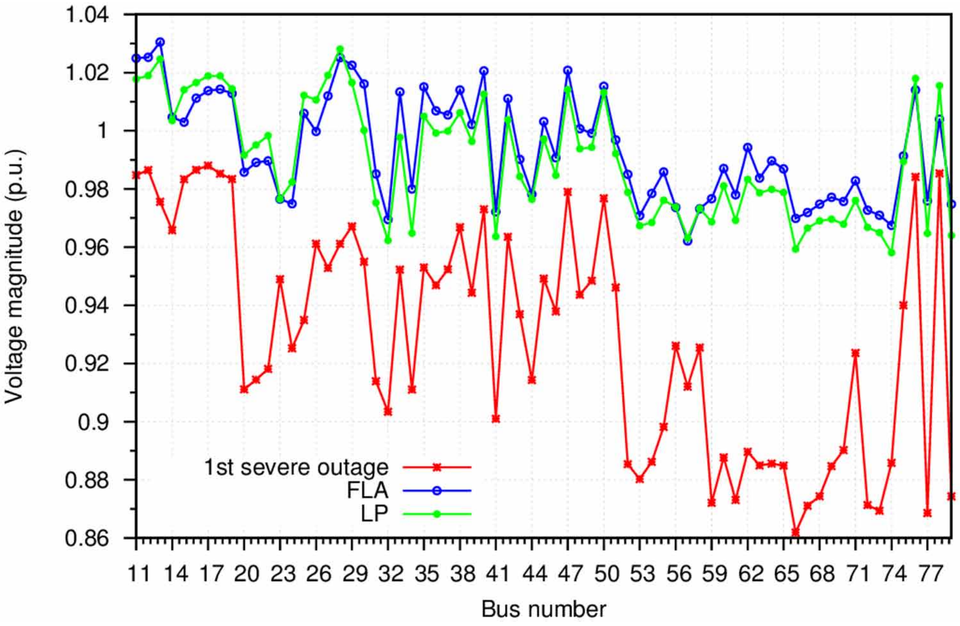
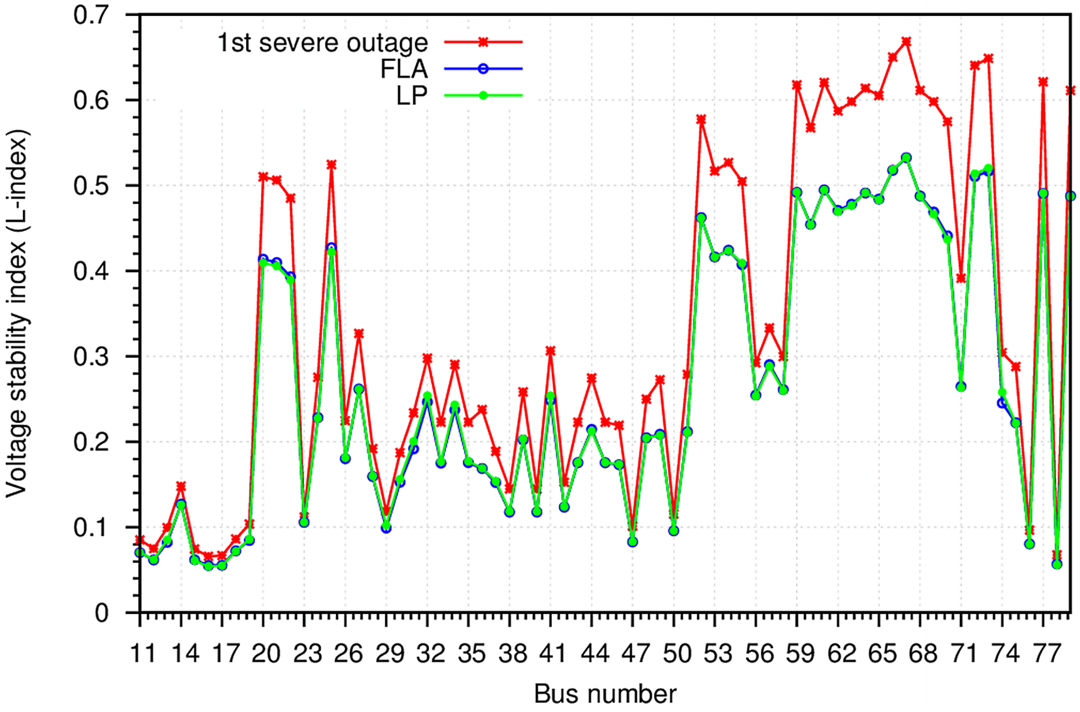


Figure 26. Voltage stability index (L-index) of SR 79-bus equivalent system with wind integration under outage/contingency condition



power from the wind farms that will be used along with other reactive power controllers from the grid for enhancing the system performance.

CONCLUSION

A fuzzy logic approach has been proposed for proper coordination of various reactive power controllers in grid connected with wind farms for voltage profile improvement. In addition, a new procedure has been incorporated in the fuzzy logic approach to address the issues associated with various controllers in grid connected wind farms. The FSWGs are also considered in the studies because of its impact on overall system voltage performance even though they do not support the system for voltage unlike the VSWGs. The simulation studies are carried out on 297-bus equivalent and 417-bus equivalent grid connected wind systems. Results demonstrated that the proposed approach is more effective in improving the system performance as compared with the conventional LP based reactive power optimization technique. The advantage of the proposed approach is that during each iteration, it uses only few reactive power/ voltage controllers of high sensitivity to achieve the desired objectives and hence, the overall computational effort is reduced. These are the desirable features for real-time implementation of the proposed approach for power system operation.

REFERENCES

Abdul-Rahman, K., & Shahidehpour, S. (1993). A fuzzy-based optimal reactive power control. *IEEE Transactions on Power Systems*, *8*(2), 662–670. doi:10.1109/59.260814

Abed, A. M. (1999). WSCC voltage stability criteria, undervoltage load shedding strategy, and reactive power reserve monitoring methodology. In *IEEE Power Engineering Society Summer Meeting* (Vol. 1, pp. 191-197). IEEE. 10.1109/PESS.1999.784345

Aghatehrani, R., Fan, L., & Kavasseri, R. (2009). Coordinated reactive power control of DFIG rotor and grid sides converters. In IEEE Power & Energy Society General Meeting (pp. 1-6). IEEE. doi:10.1109/PES.2009.5275235

Ajjarapu, V., & Lee, B. (1998). Bibliography on voltage stability. *IEEE Transactions on Power Systems*, *13*(1), 115–125. doi:10.1109/59.651622

Bansal, R. (2003). Bibliography on the fuzzy set theory applications in power systems (1994-2001). *IEEE Transactions on Power Systems*, *18*(4), 1291–1299. doi:10.1109/TPWRS.2003.818595

Central Electricity Regulatory Commission. (2010). *Indian Electricity Grid Code*. Retrieved from http://www.cercind.gov.in

Chen, N., Qian, M., Zhu, L., Yao, L., Wu, F., Chen, M., & Wang, N. (2012). A coordinated reactive power and voltage control system for wind farm grid integration. In *IEEE International Conference on Power System Technology* (pp. 1-6). IEEE.

Chen, N., Zhu, L. Z., & Wang, W. (2009). Strategy for reactive power control of wind farm for improving voltage stability in wind power integrated region. *Proceedings of the CSEE*, *10*, 019.

China Electric Power Research Institute. (2009). Retrieved from http://www.epri.ac.cn. China.

De Almeida, R. G., Castronuovo, E. D., & Peas Lopes, J. (2006). Optimum generation control in wind parks when carrying out system operator requests. *IEEE Transactions on Power Systems*, *21*(2), 718–725. doi:10.1109/TPWRS.2005.861996

Dhadbanjan, T. (1997). An expert system for alleviation of network overloads. *Electric Power Systems Research*, *40*(2), 143–153. doi:10.1016/S0378-7796(96)01146-7

Dhadbanjan, T., & Parthasarathy, K. (1995). An expert system for voltage control in a power system network. In *International Conference on Energy Management and Power Delivery* (Vol. 1, pp. 364-369). IEEE.

Dhadbanjan, T., Parthasarathy, K., & Prior, D. (1984). Improved algorithm for optimum reactive power allocation. *International Journal of Electrical Power & Energy Systems*, *6*(2), 72–74. doi:10.1016/0142-0615(84)90011-5

Dhadbanjan, T., & Yesuratnam, G. (2006). Comparison of optimum reactive power schedule with different objectives using LP technique. *International Journal of Emerging Electric Power Systems*, *7*(3), 1–31. doi:10.2202/1553-779X.1338

Divya, K., & Rao, P. N. (2006). Models for wind turbine generating systems and their application in load flow studies. *Electric Power Systems Research*, *76*(9), 844–856. doi:10.1016/j.epsr.2005.10.012

Eir Grid. (n.d.). *Eir Grid Plc*. Retrieved from http://www.EirGrid.com

El-Hawary, M. E. (1998). *Electric power applications of fuzzy systems*. Wiley-IEEE Press. doi:10.1109/9780470544457

El-Keib, A., & Ma, X. (1995). Application of artificial neural networks in voltage stability assessment. *IEEE Transactions on Power Systems*, *10*(4), 1890–1896. doi:10.1109/59.476054

Elgerd, O. l. (1982). *Electic energy systems theory-an introduction*. McGraw-Hill New York.

E.ON Netz Gmbh. (2016). *Grid Code-High and extra high voltage*. Retrieved from http://www.eon.com

Federal Energy Regulatory Commission. (2005). Principles for efficient and reliable reactive power supply and consumption staff report (Docket No. AD05-1-000). Author.

Federal Energy Regulatory Commission. (2005). Order no. 661 on interconnection for wind farms. Author.

Federal Energy Regulatory Commission. (2012). Order no. 661a (order on rehearing) on interconnection for wind farms. Author.

Freitas, W., Vieira, J. C., Da Suva, L. C. P., Affonso, C. M., & Morelato, A. (2005). Long-term voltage stability of distribution systems with induction generators. In *IEEE Power Engineering Society General Meeting* (pp. 2910-2913). IEEE.

Grid Code. (2004). *Wind power facility technical requirements - Revision 0.* Retrieved from http://www.aeso.ca

Hossain, M. J., Pota, H. R., Mahmud, M. A., & Ramos, R. A. (2012). Investigation of the impacts of large-scale wind power penetration on the angle and voltage stability of power systems. *IEEE Systems Journal*, *6*(1), 76–84. doi:10.1109/JSYST.2011.2162991

Kayikci, M., & Milanovic, J. V. (2007). Reactive power control strategies for dfig-based plants. *IEEE Transactions on Energy Conversion*, *22*(2), 389–396. doi:10.1109/TEC.2006.874215

Keane, A., Ochoa, L. F., Vittal, E., Dent, C. J., & Harrison, G. P. (2011). Enhanced utilization of voltage control resources with distributed generation. *IEEE Transactions on Power Systems*, *26*(1), 252–260. doi:10.1109/TPWRS.2009.2037635

Konopinski, R. J., Vijayan, P., & Ajjarapu, V. (2009). Extended reactive capability of dfig wind parks for enhanced system performance. *IEEE Transactions on Power Systems*, *24*(3), 1346–1355. doi:10.1109/TPWRS.2009.2023260

Kumar, V. S. S., Reddy, K. K., & Dhadbanjan, T. (2014). Coordination of reactive power in grid-connected wind farms for voltage stability enhancement. *IEEE Transactions on Power Systems*, *29*(5), 2381–2390. doi:10.1109/TPWRS.2014.2300157

Kundur, P., Balu, N. J., & Lauby, M. G. (1994). *Power system stability and control* (Vol. 7). McGraw-Hill New York.

Lof, P.-A., Andersson, G., & Hill, D. (1993). Voltage stability indices for stressed power systems. *IEEE Transactions on Power Systems*, *8*(1), 326–335. doi:10.1109/59.221224

Mamandur, K., & Chenoweth, R. (1981). Optimal control of reactive power flow for improvements in voltage profiles and for real power loss minimization. *IEEE Transactions on Power Apparatus and Systems*, (7): 3185–3194. doi:10.1109/TPAS.1981.316646

Marques, A. B., Taranto, G. N., & Falc˜ao, D. M. (2005). A knowledge-based system for supervision and control of regional voltage profile and security. *IEEE Transactions on Power Systems*, *20*(1), 400–407. doi:10.1109/TPWRS.2004.831672

Meegahapola, L., Durairaj, S., Flynn, D., & Fox, B. (2011). Coordinated utilisation of wind farm reactive power capability for system loss optimisation. *European Transactions on Electrical Power*, *21*(1), 40–51. doi:10.1002/etep.410

Moger, T. (2016). *Reactive power planning and operation of power systems with wind farms for voltage stability improvement* (Unpublished doctoral dissertation). Department of Electrical Engineering, Indian Institute of Science, Bangalore, India.

Moger, T., & Dhadbanjan, T. (2015). A novel index for identification of weak nodes for reactive compensation to improve voltage stability. *IET Generation, Transmission & Distribution*, *9*(14), 1826–1834. doi:10.1049/iet-gtd.2015.0054

Moger, T., & Dhadbanjan, T. (2016). Fuzzy logic approach for reactive power coordination in grid connected wind farms to improve steady state voltage stability. *IET Renewable Power Generation*, *11*(2), 351–361. doi:10.1049/iet-rpg.2016.0119

Moger, T., & Dhadbanjan, T. (2017). Impact of different pq models of wind turbine generating units (wtgus) on system voltage performance. *International Journal of Emerging Electric Power Systems*, *18*(4), 1–19. doi:10.1515/ijeeps-2017-0008

Nageswararao, B., & Jeyasurya, B. (1998). Fuzzy-expert system for voltage stability monitoring and control. *Electric Power Systems Research*, *47*(3), 215–222. doi:10.1016/S0378-7796(98)00068-6

National Electricity Amendment. (2007). *Technical Standards for wind and other generators connections rule.* Retrieved from http://www.aemc.gov.au

National Grid Electricity Transmission. (2009). *The Grid Code*. Retrieved from http://www.nationalgrid.com

Niebur, D. (1993). Artificial neural networks for power systems-a literature survey. *International Journal of Engineering Intelligent Systems for Electrical Engineering and Communications*, *1*, 133–158.

Pudjianto, D., Ahmed, S., & Strbac, G. (2002). Allocation of VAR support using LP and NLP based optimal power flows. *IEE Proceedings. Generation, Transmission and Distribution*, *149*(4), 377–383. doi:10.1049/ip-gtd:20020200

Scala, M. L., Trovato, M., & Torelli, F. (1996). A neural network-based method for voltage security monitoring. *IEEE Transactions on Power Systems*, *11*(3), 1332–1341. doi:10.1109/59.535674

Shareeq, M. M., Moger, T., & Dhadbanjan, T. (2014). Fuzzy logic approach to curtail number of controllers for voltage control in grid connected wind farms. In *Eighteenth National Power Systems Conference (NPSC)* (pp. 1-6). IEEE. 10.1109/NPSC.2014.7103843

Spain Grid Code. (2005). *Grid code*. Retrieved from http://www.depeca.uah.es

Srivastava, S. C., Velayutham, A., Agrawal, K. K., & Bakshi, A. S. (2012). Report of the enquiry committee on grid disturbance in northern region on 30th July 2012 and in northern, eastern & north-eastern region on 31st July 2012. Delhi: Academic Press.

Su, C.-T., & Lin, C.-T. (1996). A new fuzzy control approach to voltage profile enhancement for power systems. *IEEE Transactions on Power Systems*, *11*(3), 1654–1659. doi:10.1109/59.535711

Su, C.-T., & Lin, C.-T. (2001). Fuzzy-based voltage/reactive power scheduling for voltage security improvement and loss reduction. *IEEE Transactions on Power Delivery*, *16*(2), 319–323. doi:10.1109/61.915501

Tang, G., Xu, H., & Chen, H. (1993). An Expert System for Voltage/VAR Control of Interconnected Power Systems. In *Proceedings of the Fourth Symposium on Expert Systems Application to Power Systems* (pp. 292-295). Academic Press.

Taylor, C. W. (1994). *Power system voltage stability*. McGraw-Hill Companies.

Tinney, W., Bright, J., Demaree, K., & Hughes, B. (1988). Some deficiencies in optimal power flow. *IEEE Transactions on Power Systems*, *3*(2), 676–683. doi:10.1109/59.192922

Tomsovic, K. (1992). A fuzzy linear programming approach to the reactive power/voltage control problem. *IEEE Transactions on Power Systems*, *7*(1), 287–293. doi:10.1109/59.141716

Trichakis, P., Taylor, P. C., Lyons, P. F., & Hair, R. (2008). Predicting the technical impacts of high levels of small-scale embedded generators on low-voltage networks. *IET Renewable Power Generation*, *2*(4), 249–262. doi:10.1049/iet-rpg:20080012

Tsili, M., & Papathanassiou, S. (2009). A review of grid code technical requirements for wind farms. *IET Renewable Power Generation*, *3*(3), 308–332. doi:10.1049/iet-rpg.2008.0070

Udupa, A. N., Dhadbanjan, T., & Parthasarathy, K. (1999). An expert fuzzy control approach to voltage stability enhancement. *International Journal of Electrical Power & Energy Systems*, *21*(4), 279–287. doi:10.1016/S0142-0615(98)00049-0

Ullah, N. R., & Thiringer, T. (2007). Variable speed wind turbines for power system stability enhancement. *IEEE Transactions on Energy Conversion*, *22*(1), 52–60. doi:10.1109/TEC.2006.889625

Visakha, K., Dhadbanjan, T., & Jenkins, L. (2004). Application of upfc for system security improvement under normal and network contingencies. *Electric Power Systems Research*, *70*(1), 46–55. doi:10.1016/j.epsr.2003.11.011

Vittal, E., Keane, A., & O'Malley, M. (2008). Varying penetration ratios of wind turbine technologies for voltage and frequency stability. In *IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century* (pp. 1–6). IEEE. doi:10.1109/PES.2008.4596402

Vittal, E., O'Malley, M., & Keane, A. (2009). Impact of wind turbine control strategies on voltage performance. In IEEE Power & Energy Society General Meeting (pp. 1-7). IEEE. doi:10.1109/PES.2009.5275570

Vittal, E., O'Malley, M., & Keane, A. (2010). A steady-state voltage stability analysis of power systems with high penetrations of wind. *IEEE Transactions on Power Systems*, *25*(1), 433–442. doi:10.1109/TPWRS.2009.2031491

Wu, Q., Xu, Z., & Østergaard, J. (2010). Grid integration issues for large scale wind power plants (WPPs). In *IEEE Power and Energy Society General Meeting* (pp. 1-6). IEEE.

Yager, R. R., & Zadeh, L. A. (Eds.). (2012). *An introduction to fuzzy logic applications in intelligent systems* (Vol. 165). Springer Science & Business Media.

Yokoyama, R., Niimura, T., & Nakanishi, Y. (1993). A coordinated control of voltage and reactive power by heuristic modeling and approximate reasoning. *IEEE Transactions on Power Systems*, *8*(2), 636–645. doi:10.1109/59.260817

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, *8*(3), 338–353. doi:10.1016/S0019-9958(65)90241-X

Zheng, T., Jiao, S., Ding, K., & Lin, L. (2013). A coordinated voltage control strategy of wind farms based on sensitivity method. In IEEE Grenoble PowerTech (POWERTECH) (pp. 1-5). IEEE.

Zhu, L. Z., Chen, N., Wang, W., & Zhu, X. D. (2009). Reactive control strategy for wind farm considering reactive power command. In *International Conference on Sustainable Power Generation and Supply* (pp. 1-5). IEEE. 10.1109/SUPERGEN.2009.5348206

Zimmermann, H. J. (2011). *Fuzzy set theory—and its applications*. Springer Science & Business Media.

KEY TERMS AND DEFINITIONS

Contingency: Contingency is an outage of a transmission line or transformer that may lead to overloads in other branches and/or sudden system voltage drop.

Electric Grid: An electric grid is a network of synchronized power providers and consumers that are connected by transmission and distribution lines and operated by one or more control centers.

Fuzzy System: It is a component of machine learning techniques that takes membership values within 0 to 1 unlike crisp sets.

Optimization: A mathematical method to find the solution of a problem towards achieving better performance either in form of minimum or maximum under one or more given constraints.

Reactive Power: In electric power transmission and distribution, volt ampere reactive (VAR) is a unit by which reactive power is expressed in an AC electric power system.

Standard Deviation (STDEV): The standard deviation of the load voltage is used to quantify the amount of variation or dispersion of a set of load voltages.

Voltage Stability: Voltage stability refers to the ability of a power system to maintain steady voltage at all buses in the system after being subjected to a disturbance from a given initial operating condition.

Wind Farm: An area of land with a group of energy producing windmills or wind turbines.

Wind Turbine: A wind turbine is a device that converts the wind's kinetic energy into electrical power.

APPENDIX: COMPARISON METHOD

Linear Programming Based Reactive Power Optimization Technique

The model selected for the system voltage profile improvement is to minimize the sum of the square of the voltage deviation from desired voltage of the load buses as an objective function. It can be expressed as,

$$v^e = \sum_{j=g+1}^{n} \left(V_j^d - V_j^a\right)^2 \tag{12}$$

The selected model for the reactive power optimization uses linearized sensitivity relationships to define the optimization problem.

For this objective function, the constraints are the linearized network performance equations relating the control and dependent variables, and their limits. To improve system voltage profile, redistribution of reactive power generations in power systems is necessary (Mamandur & Chenoweth, 1981). Reactive power distributions in the system can be controlled by suitably adjusting the following control variables:

- Transformer tap settings (ΔT)
- Generator excitation settings (ΔV)
- The Switchable VAr Compensator (SVC) settings (ΔQ)

The system voltage profile and thus the stability of the system are affected by any changes brought in these variables. The changes made in these variables affect the reactive power distribution in the system and also the reactive power output from generators. The variables which are affected due to the changes in control variables are the dependent variables.

The dependent variables are:

- The reactive power output of the generators (ΔQ)
- The voltage magnitude at the buses other than the generator buses (ΔV)

All these variables also have upper and lower limits.

In mathematical form, the problem can be expressed as,

Minimize

$$v^e = Cx \tag{13}$$

Subject to

$$b^{\min} \le b = Sx \le b^{\max} \tag{14}$$

and

$$x^{\min} \leq x \leq x^{\max} \tag{15}$$

where,

C is the row vector of the linearized objective function sensitivity coefficients,
S is the linearized sensitivity matrix relating the dependent and control variables,
b is the column vector of the linearized dependent variables,
x is the column vector of the linearised control variables,
b^{max} and b^{min} are the column vectors of the linearized upper and lower limits on the dependent variables, and
x^{max} and x^{min} are the column vectors of the linearized upper and lower limits on the control variables.

The linear programming technique is now applied to the above problem to determine the optimal settings of the control variables (Dhadbanjan & Yesuratnam, 2006).

The control vector in incremental variables is defined as

$$x = \left[\Delta T_1, \ldots, \Delta T_t, \Delta V_1, \ldots, \Delta V_g, \Delta Q_{g+1}, \ldots, \Delta Q_{g+s}\right]^t \tag{16}$$

The dependent vector in incremental variables is defined as

$$b = \left[\Delta Q_1, \ldots, \Delta Q_g, \Delta V_{g+1}, \ldots, \Delta V_{g+s}, \Delta V_{g+s+1}, \ldots, \Delta V_n\right]^t \tag{17}$$

The upper and lower limits on the both the control and dependent variables in linearized form are expressed as

$$x^{\max} = \left[\Delta T_1^{\max}, \ldots, \Delta T_t^{\max}, \Delta V_1^{\max}, \ldots, \Delta V_g^{\max}, \Delta Q_{g+1}^{\max}, \ldots, \Delta Q_{g+s}^{\max}\right]^t \tag{18}$$

$$x^{\min} = \left[\Delta T_1^{\min}, \ldots, \Delta T_t^{\min}, \Delta V_1^{\min}, \ldots, \Delta V_g^{\min}, \Delta Q_{g+1}^{\min}, \ldots, \Delta Q_{g+s}^{\min}\right]^t \tag{19}$$

$$b^{\max} = \left[\Delta Q_1^{\max}, \ldots, \Delta Q_g^{\max}, \Delta V_{g+1}^{\max}, \ldots, \Delta V_{g+s}^{\max}, \Delta V_{g+s+1}^{\max}, \ldots, \Delta V_n^{\max}\right]^t \tag{20}$$

$$b^{\min} = \left[\Delta Q_1^{\min}, \ldots, \Delta Q_g^{\min}, \Delta V_{g+1}^{\min}, \ldots, \Delta V_{g+s}^{\min}, \Delta V_{g+s+1}^{\min}, \ldots, \Delta V_n^{\min}\right]^t \tag{21}$$

where,

$$\Delta T^{\min} = T^{\min} - T^{actual}$$

$$\Delta T^{\max} = T^{\max} - T^{actual}$$

$$\Delta Q^{\min} = Q^{\min} - Q^{actual}$$

$$\Delta Q^{\max} = Q^{\max} - Q^{actual}$$

$$\Delta V^{\min} = V^{\min} - V^{actual}$$

$$\Delta V^{\max} = V^{\max} - V^{actual}$$

Computation of Sensitivity Matrix [*S*]

The sensitivity matrix [*S*] relating the dependent and control variables is evaluated (Dhadbanjan et al., 1984; Dhadbanjan & Yesuratnam, 2006) in the following manner. Considering the fact that the reactive power injection at a bus does not change for a small change in the phase angle of the bus voltage. Based on this assumption, the relationship between the net reactive power change at any node due to change in the transformer tap settings and voltage magnitudes can be written as,

$$\begin{bmatrix} \Delta Q_g \\ \Delta Q_s \\ \Delta Q_v \end{bmatrix} = \begin{bmatrix} \frac{\partial Q_g}{\partial T_t} & \frac{\partial Q_g}{\partial V_g} & \frac{\partial Q_g}{\partial V_s} & \frac{\partial Q_g}{\partial V_r} \\ \frac{\partial Q_s}{\partial T_t} & \frac{\partial Q_s}{\partial V_g} & \frac{\partial Q_s}{\partial V_s} & \frac{\partial Q_s}{\partial V_r} \\ \frac{\partial Q_r}{\partial T_t} & \frac{\partial Q_r}{\partial V_g} & \frac{\partial Q_r}{\partial V_s} & \frac{\partial Q_r}{\partial V_r} \end{bmatrix} \begin{bmatrix} \Delta T_t \\ \Delta V_g \\ \Delta V_s \\ \Delta V_r \end{bmatrix} \tag{22}$$

It can also written in this form

$$\begin{bmatrix} \Delta Q_g \\ \Delta Q_s \\ \Delta Q_v \end{bmatrix} = \begin{bmatrix} A_1 & A_2 & A_3 & A_4 \\ A_5 & A_6 & A_7 & A_8 \\ A_9 & A_{10} & A_{11} & A_{12} \end{bmatrix} \begin{bmatrix} \Delta T_t \\ \Delta V_g \\ \Delta V_s \\ \Delta V_r \end{bmatrix} \tag{23}$$

where,

$$\Delta Q_g = \left[\Delta Q_1, \ldots, \Delta Q_g\right]^t,$$

$$\Delta Q_s = \left[\Delta Q_{g+1},\ldots,\Delta Q_{g+s}\right]^t,$$

$$\Delta Q_r = \left[\Delta Q_{g+s+1},\ldots,\Delta Q_n\right]^t,$$

$$\Delta T_t = \left[\Delta T_1,\ldots,\Delta T_t\right]^t,$$

$$\Delta V_g = \left[\Delta V_1,\ldots,\Delta V_g\right]^t,$$

$$\Delta V_s = \left[\Delta V_{g+1},\ldots,\Delta V_{g+s}\right]^t,$$

and

$$\Delta V_r = \left[\Delta V_{g+s+1},\ldots,\Delta V_n\right]^t,$$

The sub-matrices A_1 to A_{12} are the corresponding terms of $\partial Q/\partial T$ and $\partial Q/\partial V$ and the values are calculated from the following equations; where,

$$\frac{\partial Q_k}{\partial T_{kl}} = \frac{2}{a^3}V_k^2 y_{kl}\sin(\alpha_{kl}) + \frac{1}{a^2}y_{kl}V_kV_l\sin\left(\delta_k - \delta_l - \theta_{kl}\right) \tag{24}$$

$$\frac{\partial Q_l}{\partial T_{kl}} = \frac{1}{a^2}y_{kl}V_kV_l\sin\left(\delta_l - \delta_k - \theta_{kl}\right) \tag{25}$$

where,

k and *l* are the index for the nodes and *k* is the tap-side bus

$$\frac{\partial Q_r}{\partial T_{kl}} = 0, \quad r \neq k, l \tag{26}$$

$$\frac{\partial Q_k}{\partial V_k} = \frac{Q_k}{V_k} - B_{kk}V_k \tag{27}$$

$$\frac{\partial Q_k}{\partial V_l} = Y_{kl} V_k \sin\left(\delta_k - \delta_l - \theta_{kl}\right) \tag{28}$$

Further, transferring all the control variables to the right hand side and the dependent variables to the left hand side, and rearranging the equations.

By properly arranging the above equations, we can get,

$$\begin{bmatrix} \Delta Q_g \\ \Delta V_s \\ \Delta V_r \end{bmatrix} = \begin{bmatrix} S_1 & S_2 & S_3 \\ S_4 & S_5 & S_6 \\ S_7 & S_8 & S_9 \end{bmatrix} \begin{bmatrix} \Delta T_t \\ \Delta V_g \\ \Delta Q_s \end{bmatrix} \tag{29}$$

where,

$$S_1 = (A_1 + A_3 S_4 + A_4 S_7) \tag{30}$$

$$S_2 = (A_2 + A_3 S_5 + A_4 S_8) \tag{31}$$

$$S_3 = (A_3 S_6 + A_4 S_9) \tag{32}$$

$$S_4 = \left(A_7 - A_8 \left(A_{12}\right)^{-1} A_{11}\right)^{-1} \left(A_8 \left(A_{12}\right)^{-1} A_9 - A_5\right) \tag{33}$$

$$S_5 = \left(A_7 - A_8 \left(A_{12}\right)^{-1} A_{11}\right)^{-1} \left(A_8 \left(A_{12}\right)^{-1} A_{10} - A_6\right) \tag{34}$$

$$S_6 = \left(A_7 - A_8 \left(A_{12}\right)^{-1} A_{11}\right) \tag{35}$$

$$S_7 = \left(-\left(A_{12}\right)^{-1} A_9 - \left(A_{12}\right)^{-1} A_{11} S_4\right) \tag{36}$$

$$S_8 = \left(-\left(A_{12}\right)^{-1} A_{10} - \left(A_{12}\right)^{-1} A_{11} S_5\right) \tag{37}$$

$$S_9 = \left(-\left(A_{12}\right)^{-1} A_{11} S_6\right) \tag{38}$$

Again (29), can be written in this form;

$$\begin{bmatrix} \Delta Q_g \\ \Delta V_s \\ \Delta V_r \end{bmatrix} = \left[S\right] \begin{bmatrix} \Delta T_t \\ \Delta V_g \\ \Delta Q_s \end{bmatrix} \tag{39}$$

where [*S*] is the linearized sensitivity matrix relating dependent and control variables.

Computation of Objective Function ($v^e = C\Delta x$) Sensitivities With Respect to Control Variable

The row vector of objective function sensitivity coefficients (*C*) can be written as

$$C = \left[\frac{\partial v^e\left(x\right)}{\partial T_t}, \quad \frac{\partial v^e\left(x\right)}{\partial V_g}, \quad \frac{\partial v^e\left(x\right)}{\partial Q_s}\right] \tag{40}$$

Consider a system where, k = total number of control variables with k=1, 2...t be the number of OLTCs, t+1, t+2...t+g be the number of generator excitations and t+g+1....t+g+s be the number SVCs ($k = t+g+s$).

$$\left[\frac{\partial v^e\left(x\right)}{\partial T_m}\right] = \sum_{j=g+1}^{n} 2\left(V_j^d - V_j^a\right)\left(-S_{jm}\right) \tag{41}$$

where m = 1, 2....t for calculating the objective function sensitivities with respect to transformer taps, and S_{jm} is the corresponding sensitivity elements in (39).

$$\left[\frac{\partial v^e\left(x\right)}{\partial V_m}\right] = \sum_{j=g+1}^{n} 2\left(V_j^d - V_j^a\right)\left(-S_{jm}\right) \tag{42}$$

where $m = t+1, t+2, \dots t+g$ for calculating the objective function sensitivities with respect to generator excitations, and S_{jm} is the corresponding sensitivity elements in (39).

$$\left[\frac{\partial v^{e}\left(x\right)}{\partial Q_{m}}\right] = \sum_{j=g+1}^{n} 2\left(V_{j}^{d} - V_{j}^{a}\right)\left(-S_{jm}\right) \tag{43}$$

where $m = t+g+1 \dots$k for calculating the objective function sensitivities with respect to SVCs, and S_{jm} is the corresponding sensitivity elements in (39).