Development of A Power System Laboratory Supported By Real-time Systems

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***Abstract*—In this paper, features of a power system laboratory supported by real-time systems are outlined. These real-time systems are built using an open-source RTAI-Linux which not only offers a general purpose operating system features, but also has the hard real-time capabilities. On such a platform a transient waveform recorder is developed to capture the transient behaviour of a synchronous machine under various operating conditions such as voltage buildup and sudden 3-phase symmetrical short-circuit. Using the recorded transient waveforms, a synchronous machine model development task is carried out as per the IEEE Std. 115-2009 specified procedures. Employing such a model a time-domain simulation programme is run to tune the model parameters of the machine by comparing the simulation results against the recorded waveforms. It is also found that the transient waveform recorder provides a useful tool to visualize the synchronization and loss-of-synchronism transients either with the mains supply or with another machine. As an additional application, an open-loop excitation controller for a synchronous machine is developed which involved the realization of many hardware circuits such as inverse-cosine firing-circuit module, single-phase thyristor bridge-rectifier circuits and a DAC interfacing card. Such a laboratory is found to augment the classroom teaching of a power system dynamics course.**

***Index Terms*—RTAI, Hard real-time systems, Synchronous machine parameters, Excitation control.**

I. INTRODUCTION

A real-time system is one in which the correctness of a result not only depends on the logical correctness of the calculation but also upon the time at which result is made available [1]. Understanding the timing constraints of a real-time system, it is observed that real-time application interface (RTAI) extension to Linux operating system makes it possible to perform hard real-time controls using a commercial PC [2], [3]. Normally, hard real-time control tasks are accomplished by employing dedicated processing units, e.g., digital signal processors or microcontrollers having guaranteed interrupt latency. RTAI allows to write real-time application in Linux environment and it provides guaranteed hard real-time scheduling, retaining all the features and services of Linux operating system. It adds a small real-time kernel below the standard Linux kernel and treats the Linux kernel as a low priority real-time task. RTAI provides a large section of inter process communication and other real-time services. Communication between the real-time tasks and outside world is achieved with the help of a multifunction peripheral component interconnect (PCI) card. An important advantage of this platform is that RTAI and Linux, both are open-source software. Using such an environment many real-time applications have been successfully developed, for example, mechatronic systems [4] and a digital PID controller [5]. It is shown in [6] that for power system applications the RTAI-Linux -based systems offers a relatively low programming overheads. These real-time supported power system lab experiments are very useful for augmenting the classroom teaching [7], [8].

In this paper some real-time applications built around synchronous machines using RTAI-Linux are outlined. The following two major applications are developed:

1) A transient waveform recorder.
2) An excitation system for the synchronous machine.

Using the transient waveform recorder, operating conditions of a synchronous machine such as open-circuit voltage build up, short circuit condition and synchronization of a synchronous machine to the mains or another synchronous machine are observed. The short-circuit transient waveforms are further utilized to obtain the parameters of a synchronous machine model. Using such a model a time-domain simulation programme is run to tune the model parameters of the machine by comparing the simulation results against the recorded waveforms. Such an exercise offers an useful platform to understand the modelling issues of a synchronous machine which is generally considered to be a difficult task in a power system dynamics course at PG level.

Since excitation system is an integral part of a synchronous machine, an attempt has been made to build an open-loop controller. This involved the development of a single-phase thyristor bridge-rectifier along with the inverse-cosine-based firing-circuit module and a DAC interfacing card. These components are integrated with the RTAI-Linux to control the terminal voltage of a synchronous machine in a manual fashion. The paper is structured as follows: RTAI architecture and its features are described in section-II. The hardware used to build the necessary real-time systems is given in section-III. The procedure used to obtain the synchronous machine model parameters (including H) and the associated generator model tuning issues, recording of synchronization transient and the implementation details of an open-loop excitation system are discussed in section-IV.

II. RTAI ARCHITECTURE AND ITS FEATURES

RTAI, which is a real-time extension for the Linux kernel, provides guaranteed hard real-time scheduling, yet retains all of the features and services of the standard Linux. RTAI is now competitive from both cost and performance point of

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view with the commercial RTOS currently available such as QNX, VxWorks, etc [9]. Fig. 1 shows the architecture of RTAI. RTAI consists basically of an interrupt dispatcher. It traps the peripherals interrupts and if necessary re-routes them to Linux. It is not an intrusive modification of the kernel, it uses the concept of real-time hardware abstraction layer (RTHAL) to get information from Linux and to trap some fundamental functions. This HAL provides few dependencies to Linux Kernel. The HAL is implemented by modifying fewer than 20 lines of existing code and by adding about 50 lines of new code. This approach minimizes the intrusion on the standard Linux kernel and localizes the interrupt handling and emulation code, which is an elegant approach. Another advantage of HAL technique is that it is possible to revert Linux to standard operation by changing the pointers in the RTHAL structure back to original ones. This is quite useful when real-time operation is inactive or when trying to isolate obscure bugs. RTAI considers Linux as a background task running when no real-time activity occurs [2].

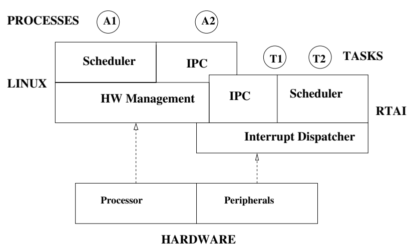

Fig. 1. The RTAI Architecture.

A real-time task in RTAI is implemented as a kernel module which is loaded into the kernel after the required RTAI core modules have been loaded. This architecture yields a simple and easily maintained system that allows dynamic insertion of the desired real-time capabilities and tasks. Following are the features of the RTAI systems [2]:

1) Inter-task communication and synchronization.
2) Communication with Linux processes.
3) Two types of mechanism to communicate between kernel-space and user-space Linux processes. These are real-time - first in first out (RT-FIFO) and shared memory (SM).
4) Timer tick interrupts.
5) Real-time in user-space-LXRT.

Using these features it is possible to write a real-time task in user-space with soft and/or hard real-time capabilities. The function *rt_make_hard_real_time()* turns a user-space process into a hard real-time process. It does this by adjusting the Linux scheduler and blocking hardware interrupts. While a hard real-time is executing user can return the process to a normal soft real-time process by calling the function *rt_make_soft_real_time()*.

III. Hardware details

In this section the hardware details of the complete setup are discussed -see Fig. 2.

- A separately excited DC motor is used as a prime-mover for the synchronous generator which has 1 kVA, 230 V, 3-phase, 50 Hz, Y connected, 4-pole, field current 1 A, as its rating. The DC motor armature/field energization is done from a three-phase AC mains through a 3-phase/single-phase auto-transformer with a built-in protection against over-speeding due to under-excitation/loss-of-field, the details of which are not presented in the paper.
- Provisions have been made to excite the filed of the alternator either from a separate DC source or using the developed excitation controller. For transient waveform recording a constant DC source is used as shown in the figure.
- The alternator 3-phase terminal voltages are measured using 230/6 V single-phase step-down transformers. The 3-phase currents including the field current are measured using current sensors. These signals are conditioned using a 7 channel signal-conditioning card with built in filters, and sample-and-hold circuits to perform simultaneous acquisition. Conditioned signals are interfaced to the computer systems via a peripheral component interconnect (PCI) card -Advantech PCI 1710HG [10].
- The real-time tasks are programmed in C, and these are dynamically loaded in the form of a kernel module in RTAI using *insmod* command and removed using *rmmod*. The PC on-board timer is used to manage the data-acquisition sampling time. The tick period of the real-time task is chosen to acquire the data periodically at a rate of 80 samples per cycle.

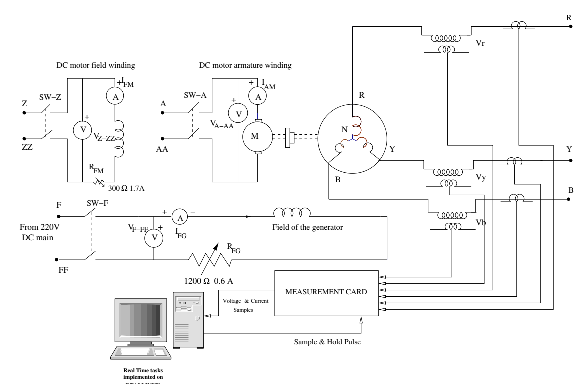

Fig. 2. Experimental setup.

Fig. 3 summarizes the various steps involved in the development of a real-time system based on the RTAI.

IV. Real-time Tasks

In this section the following real-time applications are discussed:

1) A transient waveform recorder.
2) An excitation system for the synchronous machine.

A. Transient Waveform Recorder

Using the hardware setup shown in Fig. 2 short-circuit tests are conducted on the synchronous machine. In this case,

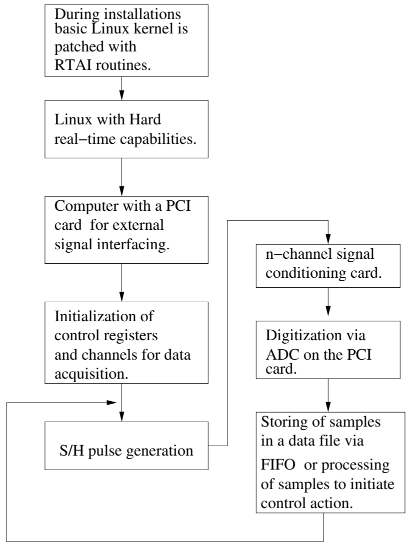

Fig. 3. Flowchart demonstrating the development of a RTAI system.

a three-phase symmetrical short-circuit is suddenly applied at the line-side terminals of the machine when the open-circuit voltage is 72 V line-to-line rms. The real-time task already inserted as a kernel module starts recording voltage and currents. The short-circuit currents captured are as shown in Fig. 4. The first sub-figure demonstrates the transients in the phase currents as it is seen in most of the text books (except for some distortions in one of the phases which may be due to the non-ideal short-circuit application). The second sub-figure shows a power frequency (0.02 s period) component in the field current during the transient condition.

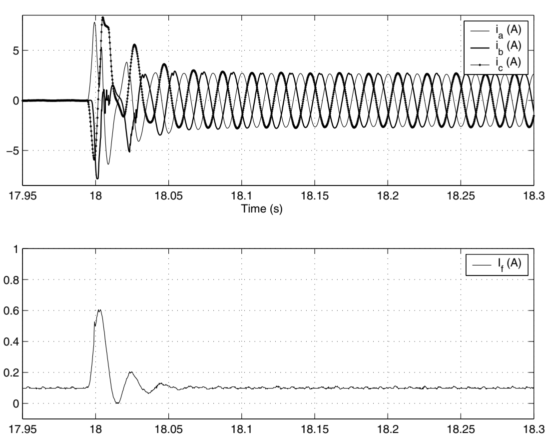

Fig. 4. Short-circuit currents of synchronous generator. Armature currents i_a,i_b,i_c; field current i_f.

1) Determination of Reactances and Time-constants of Synchronous Machines: In this case the d-axis reactances and short-circuit time-constants are estimated in an off-line analysis as per the IEEE Std. 115-2009 [11] procedures. This task is accomplished by an interactive MATLAB programme which uses one of the recorded short-circuit phase currents -see Fig. 5.

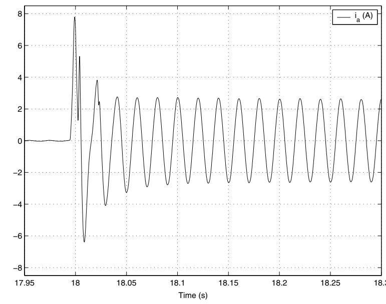

Fig. 5. Instantaneous values of armature current i_a following the fault.

The procedure to estimate the parameters of the machine is briefly outlined below [11], [12]:

1) From the peak values of the current shown in Fig. 5, the positive and negative envelops of the current waves are drawn and their ordinates are measured.
2) Neglecting harmonics, the AC component peaks I_{ac} is measured as half the difference of upper and lower envelopes.
3) The envelop of the AC components is high at the instant of short-circuit and decays ultimately to the sustained peak value I_s.
4) The crest value of the sustained armature current is then subtracted from the envelop of the AC component.
5) The remained $(I_{ac} - I_s)$ is plotted on a semi-log axis as shown in Fig. 6. The points nearly lie on a straight line except during the few cycles.
6) The straight line is extended back to *zero-time* (i.e., fault instant time) to give the initial peak value of the transient component I'_0 as shown in Fig. 6(a).
7) The value of I'_0 is subtracted from the curve $(I_{ac} - I_s)$ in the first few cycles and plotted on semi-log axis -see Fig. 6(b).
8) These values lie on a straight line and the initial peak value is taken as I''_0.
9) From the obtained I_s, I'_0 and I''_0 the d-axis reactances x_d, x'_d and x''_d are calculated.
10) The time-constants T'_d and T''_d are obtained as the time taken for I'_0 and I''_0 to decrease to 0.368 of its initial value.

NOTE: It is to be noted that from transient tests it is possible to obtain only the d-axis parameters and q-axis parameters can not be readily obtained by such tests. q-axis parameters are generally determined from the steady-state frequency-response tests on the synchronous machines [11].

Employing the procedure indicated above, short-circuit currents are acquired at different line voltages: 120 V and 105 V in addition to 72 V and the machine parameters are calculated in each cases. Considering the average value of the case studies and expressing them in per unit using the machine rating as the base values the parameters are listed in Table I.

2) Verification of the Synchronous Machine Model: For the purpose of verifying the estimated parameters, the determined parameters are fitted into a well established synchronous machine model [11] and a time-domain simulation is carried

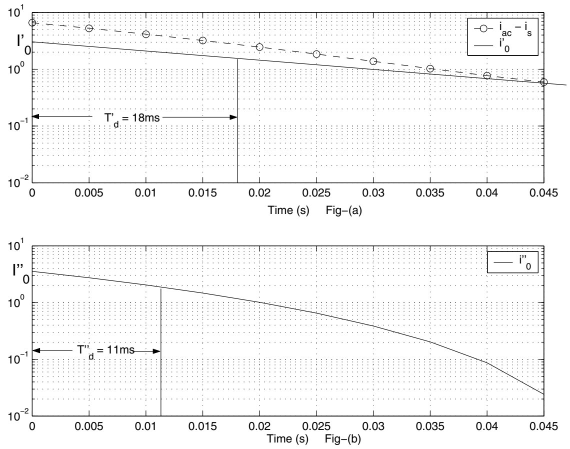

Fig. 6. Determination of short-circuit time-constants.

TABLE I
SYNCHRONOUS MACHINE PARAMETERS

x_d	x'_d	x''_d	$T'_d(ms)$	$T''_d(ms)$
0.423	0.219	0.148	18	11

out to compare the simulation results with the corresponding acquired transient waveforms. In this regard, a 2.0 model for the generator [13] is employed. Using the synchronous machine parameters (i.e., x_d, x'_d, $x^{''}_d$, T'_d and $T^{''}_d$) shown in Table I with an assumption that $x_q = x_d$, a time-domain run is carried out to simulate an open-circuit voltage build up and a sudden three-phase symmetrical short-circuit conditions. In all these simulations mechanical system dynamics are not modelled.

Open-circuit voltage build up:

The open-circuit voltage build up waveform obtained from the simulation for phase-a is shown Fig. 7. The figure also depicts the approximate raise-time of the simulated voltage (=180 ms). From this value the d-axis transient open-circuit time-constant T'_{do} is estimated (36 ms). This is verified against the tabulated data (see Table I) using a simplified relationship for T'_{do} = $T'_d(\frac{x_d}{x'_d})$ = 34 ms.

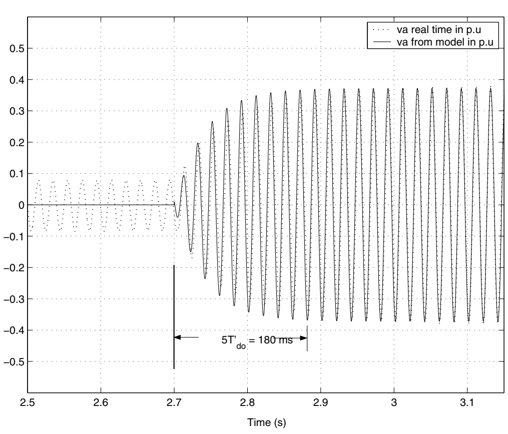

Fig. 7. Voltage build up: Comparison between simulation results and the acquired data.

A sudden three-phase symmetrical short-circuit:

Fig. 8 shows the *recorded* phase-a current in per unit for an open-circuit voltage of 105 V (line-to-line rms) in all three sub-figures. This phase-a current is compared against the simulated current for three different values of armature resistance R_a. The effect of varied values of R_a is considered (in simulation only) as it is found difficult to obtain an accurate estimate of the *effective* armature resistance from any lab tests. The figure shows the simulated phase-a current for three values of R_a. From the figure it can be seen that the simulated current pattern becomes close to the acquired waveform when R_a is set to 0.035 per unit. Such a study clearly demonstrates a parameter-tuning procedure to obtain a good model.

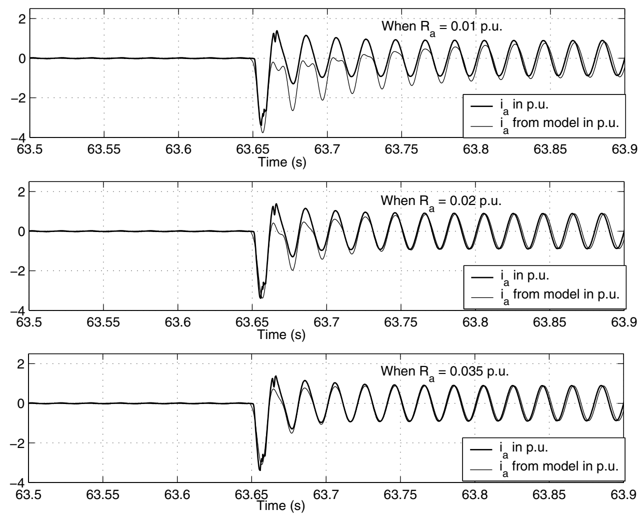

Fig. 8. Comparison between the simulated and recorded phase-a currents for different R_a values.

3) Determination of Inertia-constant of the Motor-generator Setup: Here also, the hardware setup shown in Fig. 2 is used to determine the inertia-constant of the motor-generator setup. Employing the procedure as per the IEEE Std. 115-2009 [11], the moment of inertia (in kg-m^2) of the DC motor-alternator system is determined as follows:

$$J = \frac{P}{(\frac{2\pi}{60})^2 N \frac{dN}{dt}} \tag{1}$$

Further, using the VA rating of the synchronous machine (S), the inertia constant (H) is calculated as

$$H = \frac{\frac{1}{2} J \omega_0^2}{S} \tag{2}$$

where ω_0 is the rated rotor speed in rad/s.

With dc motor armature input, P= 575.5 W, N = 1500 rpm and $\frac{dN}{dt}$ = 230 rpm/s we get H = 2.05 kJ/kVA.

The speed-running down curves are as shown in Fig. 9.

4) Recording of Synchronization and Loss-of-synchronism Transients: Using the waveform recording module synchronization and loss-of-synchronism transients of a synchronous machine are captured in the following two cases:

1) Parallel operation with mains.

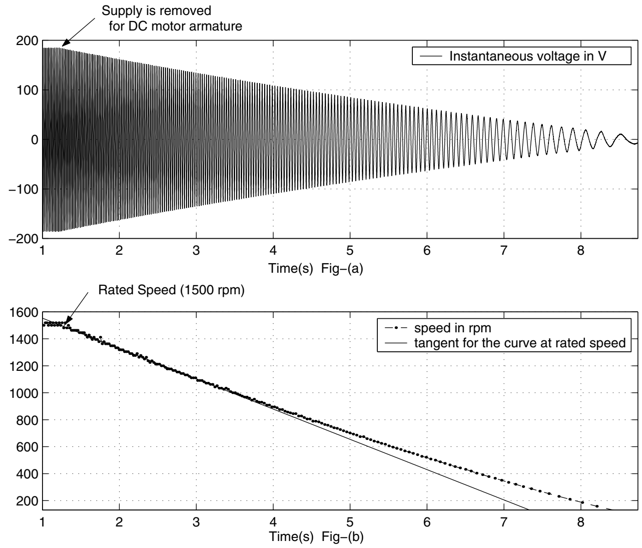

Fig. 9. Speed-running down curves.

2) Parallel operation with another synchronous machine.

Parallel operation with the mains: Here, the synchronous machine is synchronized to the mains employing the standard *dark-lamp* method. When the synchronous machine is just synchronized with the mains supply the associated terminal voltage, armature current and field current transients are observed and are as shown in Fig. 10. Note that for clarity, the terminal voltage is in pu rms, the armature current is in rms A and the field current is in A and is shifted by 4 units in the figure.

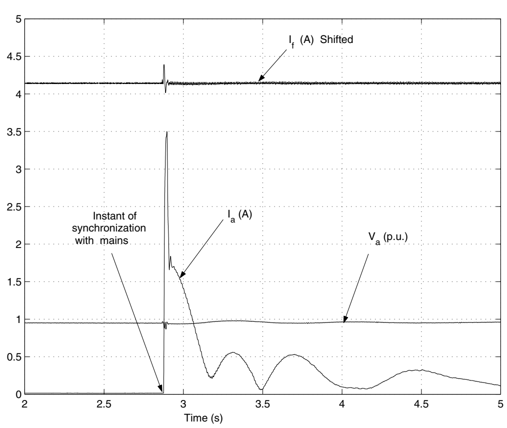

Fig. 10. Behaviour of the synchronous machine during synchronization with the mains.

After synchronization, the prime-mover input is gradually increased until a point where the machine just losses synchronism with the mains and the machine is finally tripped. During these events, the terminal voltage, armature current and field current transients are recorded and are as depicted in Fig. 11. Upto the instant of loss-of-synchronism, the armature current increase denotes the power increase, beyond this instant the current exhibits large fluctuations. However, the variation in the terminal voltage is relatively low as expected. It is to be noted that when this experiment is conducted the generator is on manual constant excitation.

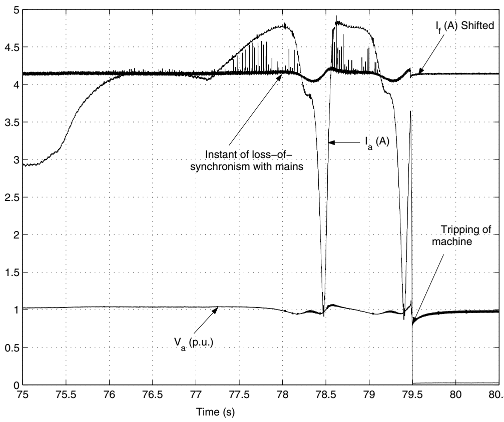

Fig. 11. Behaviour of the synchronous machine when it losses synchronism followed by its disconnection.

Parallel operation with another synchronous machine: Here the synchronous machine is synchronized to another synchronous machine of similar rating employing the standard *dark-lamp* method. After synchronization, the prime-mover input is gradually increased until a point where the machines just losses synchronism with respect to each other and the machine is finally tripped. During these events, the terminal voltage, armature current and field current transients are recorded and are as shown in Fig. 12. Note that for clarity, the terminal voltage is in pu rms, the armature current is in rms A and the field current is in A and is shifted by 3 units in the figure. Unlike that in the mains case, here both voltage and armature current exhibit violent variations denoting a large power swing between the machines. At 47.2 s the machine is tripped and it can be seen from the figure that the terminal voltage regains its no-load value. It is to be noted that when this experiment is conducted both generators are on manual constant excitation.

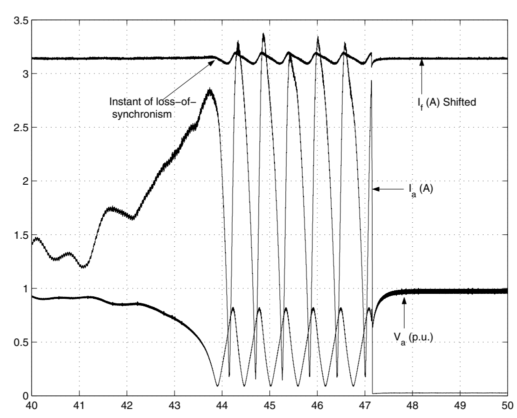

Fig. 12. Behaviour of the synchronous machine when it is losses synchronism with another machine.

B. Open-loop Excitation System for Synchronous Machine

An open-loop excitation controller is realized which involved the development of a single-phase thyristor bridge-rectifier along with the inverse-cosine-based firing-circuit module and a DAC interfacing card. These components are integrated with the RTAI-Linux to control the terminal voltage of the synchronous machine in a manual fashion.

The block schematic of the firing-angle control setup is shown in Fig. 13. The F-FF terminal in Fig. 2 is supplied from the output of the single-phase bridge-rectifier. The control voltage V_c is generated using the RTAI programming based on the pre-set firing angle. The control signal to the rectifier is in the range of (0-10) V, where 0 V corresponds to 0^o, and 10 V corresponds to 180^o firing angle. For demonstrating the open-loop control, V_{ac} is set to 70 V rms, and through the RTAI programming the control voltage is varied in a delayed fashion corresponding to different firing-angles starting from 80^o till it reaches 50^o. The corresponding field current and the rms value of the line-to-line generated voltage are captured via the transient waveform recorder and are as shown in Fig. 14.

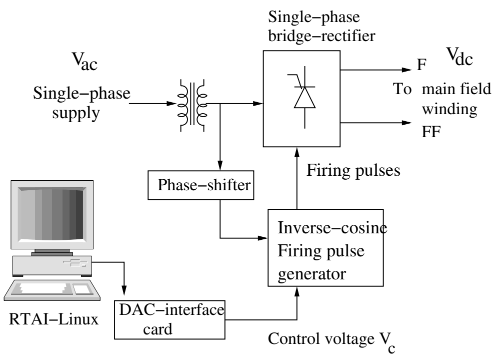

Fig. 13. Block schematic of the open-loop excitation system.

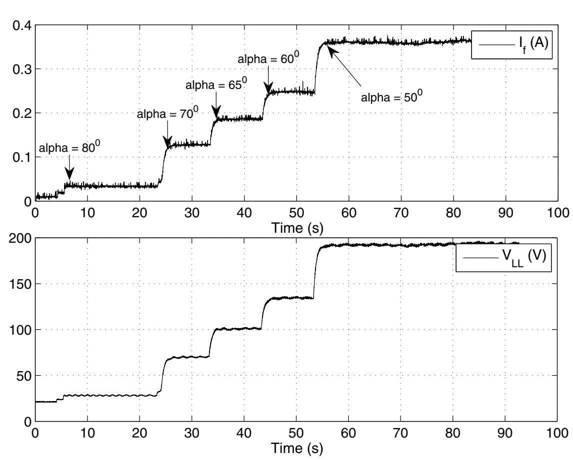

Fig. 14. Control of the field current and the terminal voltage of the alternator in open-loop.

V. Conclusion

In this paper the usefulness of synchronous machine-based experimental setups supported by real-time systems built on RTAI-Linux platform, is discussed. The application of the transient waveform recorder to analyse various dynamic behaviour of a synchronous machine is outlined. The details of an open-loop excitation controller along with the associated hardware are also presented. It is planned to extend the RTAI programming to account close-loop control of the generator field current. It can be seen that such a laboratory definitely help students to understand difficult concepts which is generally augmented only by mathematical models and time-domain simulations. Further, it should be noted that the development of such systems involve a minimal programming and hardware realization efforts.

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