Development of a PC Based Multi-Function Recorder for the Laboratory Model Power System on RTAI-Linux Platform

Deepak. M and Shubhanga K.N
Department of Electrical Engineering, NITK, Surathkal, 575025, INDIA, E-mail: knsa1234@yahoo.com

***Abstract*—This paper presents the development of a PC based multi-function recorder using an open-source real-time application interface (RTAI) in Linux environment. Here, various quantities such as three-phase real and reactive power (including the sign), power factor, RMS value of the voltage and currents and frequency are estimated employing the instantaneous samples of 3-phase voltages and currents. Such a setup not only permits easy handling of plots in an off-line environment, but also helps to visualize the operating conditions of machines which are generally learnt only by mathematical models and time-domain simulations. In the paper, this aspect has been demonstrated by acquiring the operating conditions of a lab synchronous machine when it is subjected to loss-of-synchronism and loss-of-excitation. Further, since the system provides values of quantities in real-time, it is found that such a set up can be upgraded to a protective relaying system, for example, reverse power detection relay, and even for controller implementation.**

***Index Terms*—Real-time systems, Synchronous machines, Loss-of-synchronism, Loss-of-excitation.**

I. INTRODUCTION

Developments in digital technology has made a real-time system to be an integral part of any modern control and monitoring application systems. Normally, real-time control tasks are accomplished by employing dedicated processing units, e.g., digital signal processors or microcontrollers having guaranteed interrupt latency. Where as the real-time application interface (RTAI) extension to Linux operating system [1] 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 [3]. An important advantage of this platform is that RTAI and Linux, both are open-source software and with very little C-type codes real-time requirements can be achieved using a commercial PC. Understanding the advantages of such systems [4]-[6], in this paper, a multi-function recorder application is developed using RTAI-Linux.

Using the multi-function recorder, operating conditions of a synchronous machine are monitored through the measurement of three-phase real and reactive power (including the sign), power factor, RMS value of the voltage and current, frequency (by phase-locked-loop and voltage zero crossing techniques) and field current. These quantities are calculated in real-time employing the acquired instantaneous samples of 3-phase voltages and currents. All calculations are done by writing codes in the Linux environment. These programmes are executed using the RTAI functions by inserting them as real-time modules. The hardware setup involves voltage and current transducers, signal-conditioning cards and sample-hold pulse interfacing cards and PCI card. Many case studies have been carried out on lab synchronous machines to know their transient and steady-state operating conditions. These include standalone load tests, synchronization, auto-plotting of V-curves, Λ-curves and PV-curves, load rejection tests, loss-of-synchronism and loss-of-excitation conditions. Such an exercise offers an useful platform to visualize the behaviour of synchronous machines which is generally considered to be a difficult task in a power engineering course at UG and PG levels [7].

The paper is structured as follows: RTAI features and its installation details are described in section-II. The hardware used to build the necessary real-time systems is given in section-III. The computation procedures used to evaluate different quantities are briefed in section IV. In section V, some sample plots pertaining to synchronous operation of generator and loss-of-field condition on a synchronous machine are presented to demonstrate the usefulness of the developed application.

II. RTAI

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/removal of the desired real-time capabilities and tasks. The steps followed to install RTAI are briefed below [1].

- Select the version of RTAI, the Linux kernel version to use, and a Linux distribution that uses that kernel. One can choose them in any order, but its important to end up using a consistent set. For example, with Fedora Linux distribution, to install RTAI 3.5 , first we need to install Fedora 7 distribution which has Linux Kernel version 2.6.21. A lower version of kernel 2.6.19 chosen for which the RTAI patch is available [5], [8]. It is found that such a selection can be made even with Ubuntu Linux distribution.
- Install the Linux distribution.
- Download a clean version of the Linux kernel from the Linux distribution sites.
- Download the tar file for the RTAI release.
- Unpack and uncompress the files.

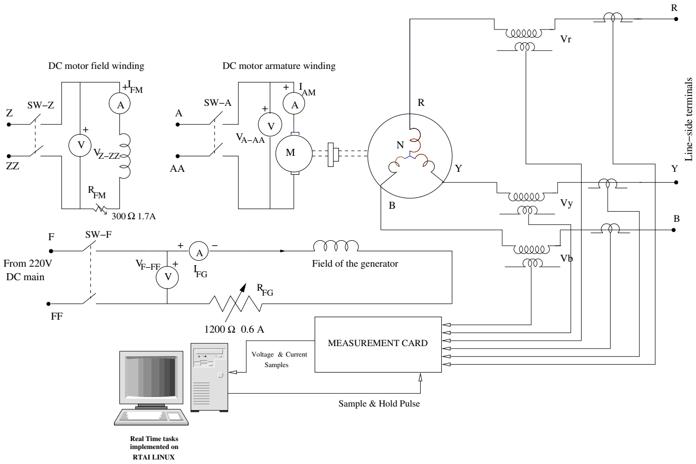
978-1-4673-2272-0/12/$31.00 ©2012 IEEE

- Using the patch file in the RTAI release that corresponds to the kernel source you have downloaded, patch the kernel source to incorporate the RTAI modifications.
- Generate a configuration file that suits the machine you are going to run on.
- Build and install the Linux kernel.
- Configure, build and install RTAI.
- Check for consistency of the installed files.

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 onboard timer is used to manage the data- acquisition sampling time.

III. HARDWARE DETAILS

In this section the hardware details of the complete setup are discussed -see Fig. 1. 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 measuring card consists of signal-conditioning cards for both voltage and current signals. These cards receive sample-and-hold pulses from the PC whose periodicity is set by the tick period of the real-time task. The tick period of the real-time task is chosen to acquire the data periodically at a rate of 40 samples per cycle. Conditioned signals are interfaced to the computer systems via a peripheral component interconnect (PCI) card -Advantech PCI 1710HG [9].



Alternator:$1kVA, 230V, 3-\phi, 50Hz, Y connected, 1500rpm.$

Fig. 1. Block diagram of data acquisition from synchronous machine.

IV. COMPUTATION OF VARIOUS QUANTITIES

Using the developed hardware set up -see Fig. 1, samples of 3-phase instantaneous voltages and currents are acquired. From the acquired samples different quantities such as real power, reactive power, power factor, frequency, RMS values of voltage and current for the machine are calculated. In the following lines the calculation methods employed to evaluate these quantities are described.

A. Frequency Measurement System

The frequency of the input signal is evaluated by the following two methods:

1) Phase Locked Loop (PLL).
2) Zero crossing (ZC) method.

1) Phase Locked Loop: In this method the frequency of the input signals is tracked by implementing a conventional three-phase PLL system in the synchronous reference frame as shown in Fig. 2.

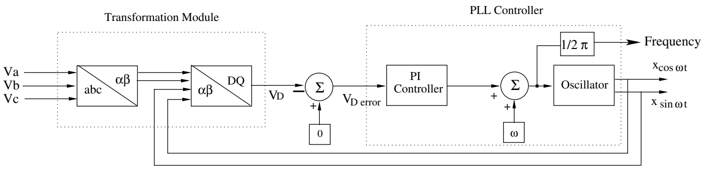


Fig. 2. Block diagram of PLL.

Let v_a, v_b and v_c are the three-phase voltage of fundamental frequency ω. These phase voltages which are in abc- frame are converted into the stationary $\alpha\beta$ -frame by using the power-variant transformation. Thus we have,

$$V_\alpha = v_a \tag{1}$$

$$\tag{2}$$

$$V_\beta = \frac{v_c - v_b}{\sqrt{3}} \tag{3}$$

This assumes that $v_a + v_b + v_c = 0$.
DQ-components are obtained from $\alpha\beta$-frame using the following transformation

$$\begin{bmatrix} V_D \\ V_Q \end{bmatrix} = \begin{bmatrix} x_{sin\ \omega t} & x_{cos\ \omega t} \\ x_{cos\ \omega t} & -x_{sin\ \omega t} \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{4}$$

where $x_{sin\ \omega t}$ and $x_{cos\ \omega t}$ are the solutions obtained having solved the following differential equation governing the harmonic oscillator.

$$\ddot{x} = -\omega^2 x \tag{5}$$

The above equation is numerically solved by employing the following equation which over-comes the problem of integrator drift

$$x_{n+1} = x_n + (\omega \times \Delta t) y_n \tag{6}$$

$$y_{n+1} = y_n - (\omega \times \Delta t) x_{n+1} \tag{7}$$

where Δt is the sampling interval.
The frequency information is tapped as shown in Fig. 2.

2) Zero Crossing Method: In this method of frequency measurement, a counter is set up which counts the number of samples covered in one complete cycle of the input signal based on the negative-to-positive transition of the sample value. Using the counter value, k, the frequency of the input signal is measured as $\frac{1}{k \times \Delta t}$. The measured frequency data is passed through a first order filter to smoothen the plot.

B. Power Measurement

Three-phase active and reactive powers are measured using instantaneous samples of 3-phase voltages and currents.

1) Active Power calculation: Let $v_a,\ v_b$ and v_c be the instantaneous phase voltages, and $i_a,\ i_b$ and i_c be the instantaneous line currents of a Y-connected system at any time instant. Then 3-phase active power, P, is calculated as given below.

$$P \ = \ [v_a i_a + v_b i_b + v_c i_c] \tag{8}$$

2) Three phase Reactive Power calculation: It is well known that the reactive power is a fundamental frequency sinusoidal steady-state concept. However, with the development of power electronic systems in reactive power compensation applications, the definition of the reactive power has taken different forms [10]. In the current implementation, 3-phase reactive power, Q is calculated as given below.

$$Q = \frac{1}{\sqrt{3}}[v_a(i_c - i_b) + v_b(i_a - i_c) + v_c(i_b - i_a)] \tag{9}$$

Note that the above equation for reactive power provides the value including the sign of the reactive power.

Once the value of active power and reactive power is evaluated the power factor can be calculated as

$$\text{Power Factor } = \tan^{-1}(\frac{Q}{P}) \tag{10}$$

C. Voltage and Current Measurements

At any time instant the sampled values of phase voltages, $v_a,\ v_b$ and v_c are used to calculate the RMS value of line-to-line voltage as given below

$$V_{RMS} = \sqrt{(v_a^2 + v_b^2 + v_c^2)} \tag{11}$$

Similarly, the phase currents are calculated from the samples as

$$I_{RMS} = \frac{1}{\sqrt{3}}\sqrt{(i_a^2 + i_b^2 + i_c^2)} \tag{12}$$

NOTE: All data points obtained for different quantities are passed through a first order filter to obtain smooth plots. The transfer function of the filter is given by

$$\frac{y(s)}{u(s)} = \frac{1}{1 + s\tau} \tag{13}$$

The above filter function is realized in discrete time-domain by employing Forward-Euler numerical integration technique as follows:

$$y_{n+1} = y_n + \frac{\Delta t}{\tau}(u_n - y_n) \tag{14}$$

where, τ is the filter time-constant and Δt is the time step of integration.

To demonstrate the RTAI programming issues, an incomplete set of codes are listed below:

```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/stddef.h>
#include <linux/pci.h>
#define N     40
#define TICK_PERIOD 0.02*1000000000/(N)

static RT_TASK rt_task;

//RMS value calculation
vrms=sqrt((va*va)+(vb*vb)+(vc*vc));

//Implementing first order filter with time
        constant 'toe'//
vfilter_new= vfilter_old +
        +((.02/40)/toe)*(vrms-vfilter_old);
vfilter_old=vfilter_new;
```

The programme module is compiled using `Makefile`. Then the module is inserted in the terminal by using `insmod` command and later it is removed by `rmmod` command.

V. EXPERIMENTAL OBSERVATIONS

In this section, results of the following two experiments conducted in the lab, are presented:

1) Synchronous machine synchronized to lab mains.
2) Synchronous machine synchronized to another machine.

[12], [11] In each of the above cases, many case studies are carried out to illustrate the usefulness of the multi-function recorder. As and when the new samples of voltage and currents are available, the RTAI module computes all quantities in real-time and stores the estimates in the form of data files. These data files are used in an off-line environment to plot the desired variables.

A. Synchronous Machine Synchronized to Lab Mains

In this case the synchronous machine is synchronized to the lab mains employing the standard *dark-lamp* method. Having synchronized the machine, the various events such as increase of real power at 40 s, increase of field current (during 80 to 100 s), decrease of field current (during 100 to 140 s) and reducing the real power out to zero and entering into motor operation (above 150 s), are created -see Fig. 3. Also note that during the motor operation (where real power is negative) the machine continues to deliver reactive power (a positive Q) to the mains.

1) V- and Inverted V- Curves: From the estimates of the power factor and RMS value of the armature current, the well known V- and inverted V-curves are drawn as shown Figs. 4 and 5.

B. Synchronous Machine Synchronized to Another Machine

Here the synchronous machine is synchronized to another synchronous machine of similar rating employing the standard *dark-lamp* method. In this the following two cases are discussed:

- Loss-of-synchronism.
- Loss-of-excitation.

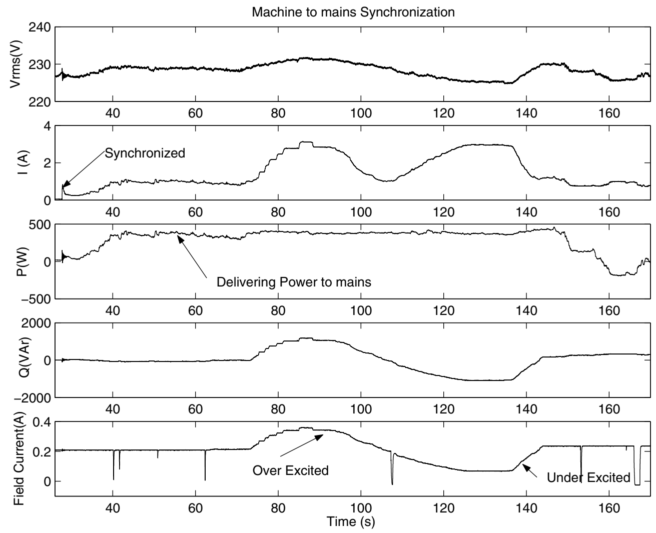


Fig. 3. Synchronization of alternator to lab mains.

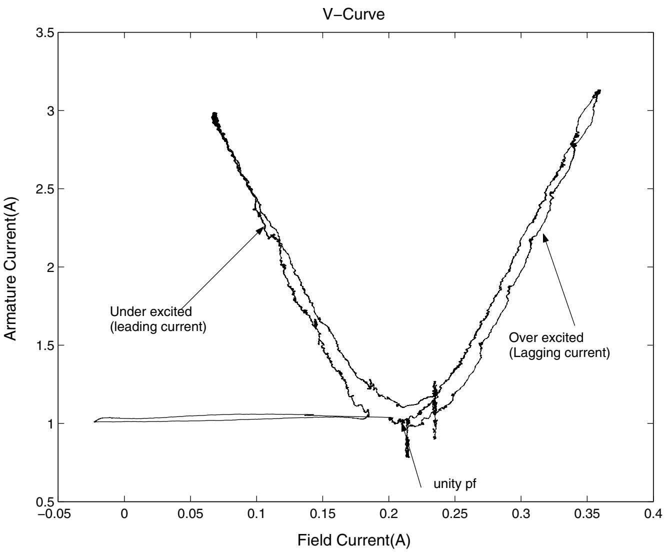


Fig. 4. V-curves for a given real power of 410 W.

1) Loss-Of-Synchronism: Having synchronized the machine, the following events are carried out: (a) The mechanical input to the machine is increased at 23 s. Note that this resulted in raise of frequency of the combined machine set. (b) During 40 to 60 s the filed current is increased. (c) during 70 to 90 s the filed current is decreased. (d) During 90 to 100 s the mechanical input is reduced to zero. (e) From 100 to 140 s a resistive load is gradually applied on the combined set. This load is picked up by the set due to self-governing action of the DC- motor. However, this results in decrease of frequency. (f) At 160 s the external load is reduced to zero. (g) To create a loss-of-synchronism case, the mechanical input of the machine is gradually increased from 165 s onwards. When the real power output of the machine is around 250 W the machine losses synchronism leading to wild oscillation of variables - see Figs. 6 and 7.

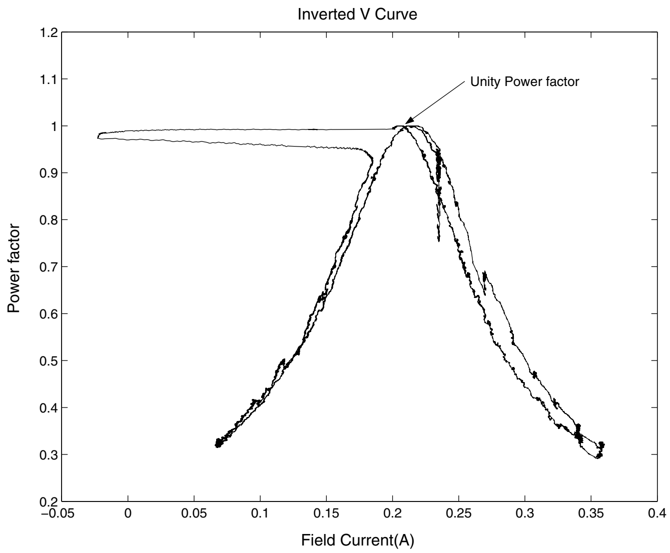


Fig. 5. Inverted V-curves for a given real power of 410 W.

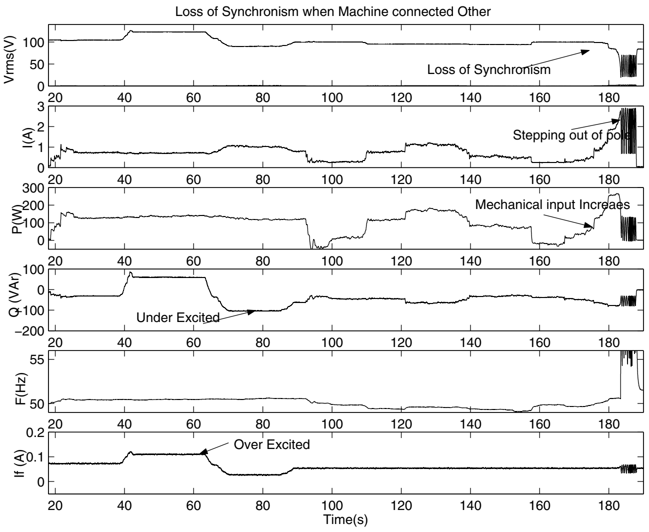


Fig. 6. Parallel operation of the machine with another machine.

The loss-of-synchronism along with the voltage collapse phenomenon is depicted in Fig. 8 where the terminal voltage is plotted against the real power delivered. This plot appears to be similar to 'nose'-curve discussed in literature.

Fig. 9 shows the frequency estimates obtained by the PLL and the zero crossing (ZC) methods. It is clear from the figure that during the steady-state condition both the methods provide almost identical estimates. However, during loss-of-synchronism condition, the frequency estimated by the ZC method is much larger due to excessive swings in the phase-voltage. Whereas, the PLL-based method does not demonstrate such a behaviour.

2) Loss-Of-Excitation: In this case, after synchronizing the machine to another machine, two operating conditions are considered based on the real power delivered by the machine.

1) P is set to 80 W.

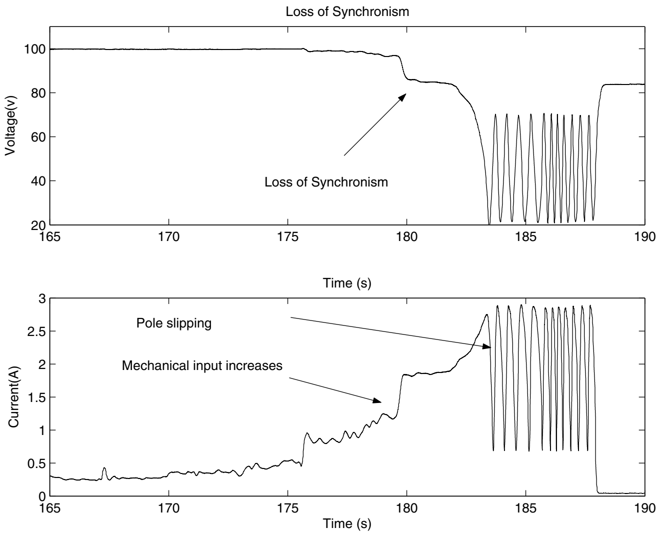


Fig. 7. Voltage and currents during loss-of-synchronism.

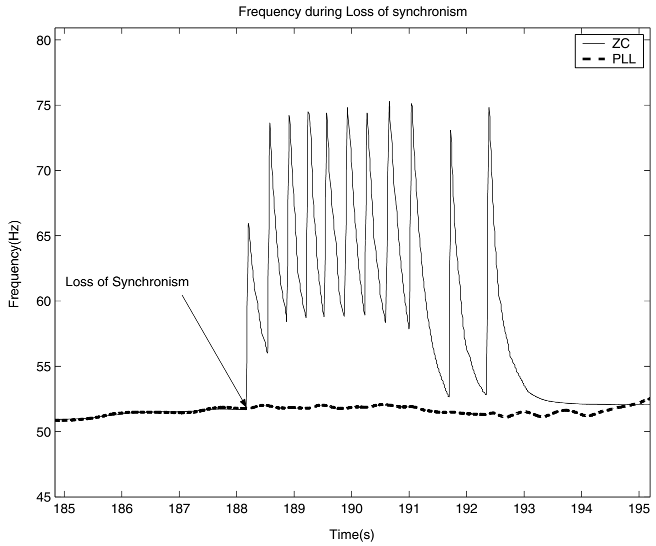


Fig. 9. Estimation of frequency during loss-of-synchronism.

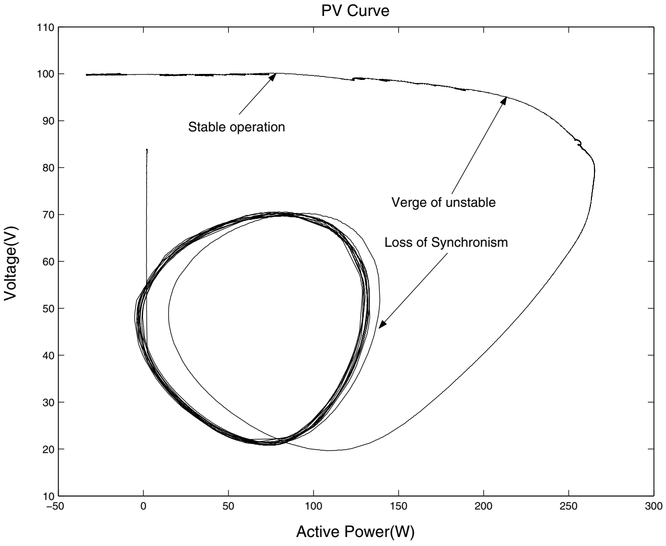


Fig. 8. PV-curve following loss-of-synchronism.

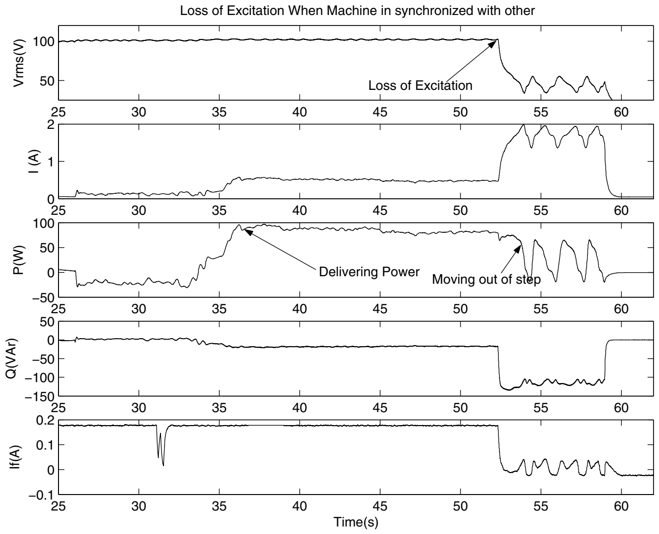


Fig. 10. Plots related to loss-of-excitation P = 80 W.

2) P is set to a low value, say 20 W.

When the machine is operating under steady-state, the synchronous machine field supply is disconnected leaving behind a shorted field terminals through a free-wheeling diode. For P=80 W case the plots are shown in Fig. 10.

As it can be seen from the figure that the machine losses synchronism after the field is removed. This leads to a large fluctuation of machine variables, and finally the machine is disconnected. However, the situation is quite different when P is set to 20 W- see Fig. 11. From the figure it is clear that the machine continues to deliver a real power close to 20 W even after the the field is disconnected. At the same time it starts absorbing reactive power from the other machine. This demonstrates the induction generator operation of the machine at low power levels. [12], [11]. Also note that the power factor estimates are quite erroneous when the real power is relatively small.

VI. CONCLUSION

In this paper, features of an RTAI-based multi-function recorder developed to augment the laboratory experiments conducted on a scaledown model of power system at Department of Electrical Engg., NITK Surathkal, are presented. It permits recording of various quantities such as real and reactive power, RMS values of voltage and current and frequency. Such a system not only help the UG and PG students to visualize the operating conditions of machines, but also facilitates easy drawing of plots like V-curve and inverted V-curve without requiring to make a manual note of the data points. In addition, it provides a platform to understand difficult concepts such as loss-of-synchronism/loss-of-excitation, which is generally augmented only by mathematical models

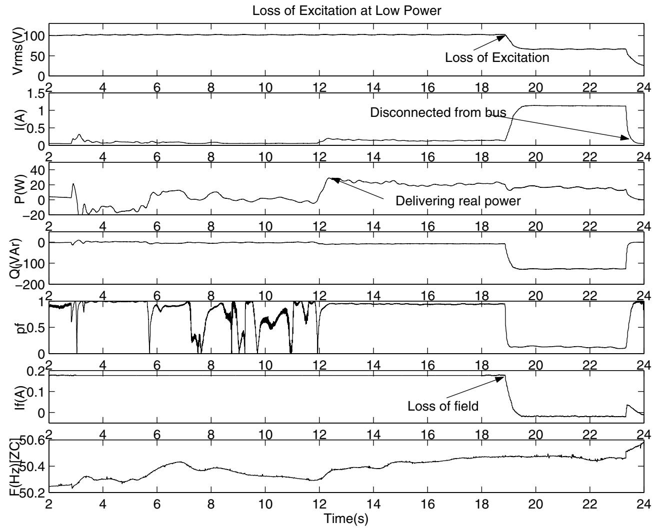


Fig. 11. Plots related to loss-of-excitation P = 20 W.

and time-domain simulations. These events cannot be tracked via analog meters because of their low bandwidth. Further, since in these systems quantities are computed in real-time, the same setup can upgrading to realize protective relays without much additional efforts. The presented real-time system can be used for any other purposes such as controller development with a minimal programming and hardware realization efforts.

REFERENCES

[1] Real Time Application Interface. [online]. Available: http://www.rtai.org

[2] Pasi Sarolahti, *Real-Time Application interface*. University of Helsinki, Department of Computer Science, 2001.

[3] Aeolean Inc.,"Introduction to Linux for Real-Time Control", National Institute of Standards and Technology, Version 2.0.0,2002.

[4] R. S. Guerra, H. J. Goncalves Junior, W. F. Lages, *A Digital PID Controller Using RTAI*, Federal University of Rio Grande do Sul, Electrical Engineering Department, 2005.

[5] Chetana Savithri, "Real Time Control of Power Electronics Controllers in a Scaled Power System", Master's thesis, Department of Electrical Engineering, Indian Institute of Technology, Bombay, July, 2008.

[6] D. Surendra , K. N. Shubhanga, *Development of A Power System Laboratory Supported By Real-time Systems*, International Conference on Power and Energy Systems(ICPS)-2011.

[7] T.W. Gedra, An Seungwon, Q. H. Arsalan and S. Ray "Unified power engineering laboratory for electromechanical energy conversion, power electronics and power systems", *IEEE Trans. on Power Systems*, Vol. 19, No. 1, pp. 112- 119, Feb., 2004.

[8] Danda Surendra, "Development of Real-time Systems Using RTAI-Linux For Power System Applications", Master's thesis, Department of Electrical Engineering, National Institute of Technology Karnatka,Surathkal, July 2011.

[9] *PCI-1710 Series User's Manual,* Advantech. [Online]. Available: http://www.advantech.com/support.

[10] K.Srinivasan,C.T. Nguyen.,*Instantaneous Three -Phase Reactive Power for Digital Implementation:Definition and Determination*,Proceedings of the IEEE Vol.66 No.8 Aug., 1978.

[11] P. Kundur, *Power System Stability and Control*, McGraw-Hill Inc., New York, 1994.

[12] K.R. Padiyar, *Power System Dynamics - Stability and Control*, BS Publications, Hyderabad, India, 2006.