

PHASOR MEASUREMENT UNIT BASED DATA ACQUISITION AND TRANSFER SYSTEM FOR THE SOLUTION OF THE ECONOMIC DISPATCH PROBLEM USING THE REAL TIME DIGITAL SIMULATOR

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Abstract: *The electric power utilities play a vital role in the generation, transmission and distribution of the electrical power to the end users. The power utilities generally face two major issues – firstly, power systems are expected to operate close to the maximum capacity, and secondly, there is a need for accurate monitoring and control of the power system network using the modern technological advances together with their associated configuration tools. These two issues are interconnected as better monitoring allows for better control of the power system. The development of the new standard-based power system technologies contribute to concept of building of a smarter grid. The challenge is that this process requires the development of new control and operation architectures and methods for data acquisition, data transfer, and control computation. These methods require data for the dynamic state of the entire power system in real-time, which allows for the introduction of synchrophasor-based monitoring and control of the power system. This paper describes the research work for integration of the newer existing power system technologies to build fully automated systems for the real-time solution of power system energy management problem, incorporating data measurement and acquisition, data transfer and distribution through a communication network, and data storage and retrieval in one complete system. The paper further details the developed methods, algorithms, procedures, software and hardware tools for implementation of a lab-scale prototype of the power system and the acquisition and transfer of the data to the control center in order to allow for the solution of the optimal power dispatch problem in real-time using real-time data.*

The developed prototype systems are tested for the five-bus power system model, and the system operation test results are presented. The model is developed within the RSCAD software environment and the output signals are fed to the software-based PMU. The data from the GTNET-PMU is transferred to the Phasor Data Concentrator (PDC) using the Ethernet. The developed data acquisition, data transfer, data retrieval and data storage system algorithms and software programs can be expanded for use in the power grid energy management system for the economic dispatch solution in regional or national control centers, smart grid applications,

educational courses and postgraduate research at universities.

Key words: *Smart grid, Synchrophasor, Phasor Data Concentrator, Real Time Digital Simulator, Data Acquisition system, Power System monitoring and Control, Economic Dispatch problem and Lagranges method.*

1. Introduction

The current technological developments to address the challenges of the introduction of a smarter grid include, sensing and measurement, integrated communication system, improved control strategies, interfaces and knowledge-based decision-making systems in [1] and [2]. The need for further development of the above technologies requires an integrative approach and knowledge not only about the physical power system, but also about the communication architecture and the control of the connected power system components. Additionally, the requirements for the operation of the smart grid are that it acts as an autonomous, fully automated and optimized system. The challenges brought about by these needs and requirements include which existing methods, technologies, hardware and software tools are applicable that can further be developed, or which new ones require investigation and implementation. This means that there is a need for the development of new techniques for interconnectivity of systems and approaches between the power system elements, and a detailed understanding of the new approaches, methods, algorithms, hardware and software necessary to achieve full integration of the operation of the smart grid.

The energy management systems are one of the main parts of the smart grid as they control and reduce the uncertainty into the daily operation of the power system, utilizing various methods and tools for monitoring, visualization, state estimation, real-time stability assessment, restoration, optimisation of power flow, economic dispatch, real-time control, etc. Among those control strategies, this paper provide the solution

of the economic dispatch problem in real-time. At present the Energy Management System (EMS) operation is performed by existing SCADA systems, which supervise, control and manage the generation, transmission and distribution systems. The operation of the SCADA systems does not satisfy today's requirements for fast information in order to produce and implement real-time control in the power system. This situation is due to the fact that the SCADA system is designed and implemented using the principles of the older technology,[3] for measurement, communication and control as follows: The 3-phase current and voltage signals from the CTs (Current Transformers) and PTs (Power Transformers) are sampled and sent to the energy management system only represented by their magnitude and the line active and reactive powers. The measurement window is large, which produces data that is not as accurate with the system changes. The assumption that during the window period the load parameters will change and the system will remain constant and is not valid during the measurement window.

The SCADA system does not allow measurement of the power system voltage and current angles and does not consider synchronized wide area measurement. Analysis of the system status is based on a multiple power flow approach, which creates a computational burden that is not fast enough for real-time implementation. The existing situation is that critical data is required to monitor the system during transients and disturbances which require fast synchronized data in order to capture the system dynamics. Then, based on these data, creating a real-time situational awareness, it is possible to implement fast real-time control. Online monitoring of the currently large interconnected power systems is important to visualize the network in real-time, which has become possible with the advent of the synchrophasor technology. The phasor measurement unit provides real-time measurement data such as bus voltages and branch current phasors from remote locations to a phasor data concentrator at the control centre that is synchronized and time-stamped in [1] and [2]. The satellite-based Global Positioning System (GPS) is used to synchronize all the PMUs, which are located at different buses with one pulse per second (1 pps) trigger, having an uncertainty in the order of nanoseconds. The sampling clock of the PMU is synchronized to the Universal Time Coordinator (UTC) signals to enable synchronized phase angle measurement from the instantaneous values of voltage and current.

This paper uses a software-based PMU, which is simulated within the RSCAD software interface of the RTDS. The data streams are transmitted to the software-based Phasor Data Concentrators (PDCs),[4] which are external to the Simulator [5-6] and is accomplished using the PMU firmware option for the

GTNET card, which provides synchrophasor output data streams according to the IEEE C37.118 standard, [7-11]. The RTDS GTNET PMU model can represent and provide for up to 8 PMU outputs with symmetrical component information such as three-phase voltage and currents using the User Datagram Protocol (UDP) or the Transmission Control Protocol (TCP) connections. The reporting rate of each PMU can be set individually between 1 and 60 frames per second. The need for high resolution synchronized data is addressed by the Phasor Measurement Units (PMUs), which are sophisticated digital recording devices capable of exporting GPS-synchronized data with a high sampling rate [11]. This fact supported the approach to take decisions for power system operation based on steady-state data from a local area to be shifted to paying attention to the system dynamic behavior in a global or wide area. The use of the synchrophasor data requires a proper, fast, reliable, and safe communication network between the PMUs and the control center that supports both the existing functionalities and the future operational requirements to be developed. Using synchronized data at the control center requires restructuring of the available methods and software algorithms for solution (calculation) of the energy management problems and the transfer of the obtained control actions of the elements of the power systems.

On the basis of the above, it can be concluded that there is a need for interdisciplinary research to develop a close integrated framework of the latest achievements in the field of measurement, communication, optimisation and control of power systems. This paper concentrates on research work in this field following the principles of the PMU measurement based Smart Grid system and aiming to produce real-time working prototypes implementing a real-time solution of the power dispatch optimisation problem for given power networks. The case studies for the implementation for such a system have been developed in the laboratory of the Centre for Substation Automation and Energy Management Systems (CSAEMS), at the Cape Peninsula University of Technology, to demonstrate to the power utilities how such a measurement, communication and control optimisation framework can operate from one side, and to support the interdisciplinary education and research for graduate and postgraduate control and power system engineering students in the field of the new power system monitoring, protection, automation and control technologies, from the other side. At present the educational programs at universities are very narrow specialised programs, and the engineers produced here are not fully equipped to meet the challenges presented by the new smarter grid. A few of the papers reviewed solve the problem for dispatch of power for a real system and using real-time data and optimisation in [12-14]. The required changes to the power production are also not communicated in real-time to the power

producers. The reason for these problems are that communication systems for data acquisition, data transfer, data storage, and data retrieving in real-time have not been developed yet. The aim of this paper is the development of lab-scale variants of the power system supporting the real-time data acquisition and data transfer using the available hardware and software to demonstrate the possibilities for the real-time solution of the optimal power dispatch problem using real-time data. A lab-scale variant of the system for data acquisition and data transfer using the GTNET card Phasor Measurement Unit (PMU) synchrophasor data is developed to investigate different possibilities for capturing the power system data from the Real-Time Digital Simulator (RTDS) simulation model and to transfer the data to a local or remote control center using the software-based PDC in [4]. The investigations are done for the five-bus power system model in [12], which are constructed within the RSCAD software environment, which is the software suite of the RTDS.

This paper is structured with the introduction as presented above; the implementation of a lab scale data acquisition system is given in section 2; the problem formulation and algorithm for the solution of the dispatch problem is presented in sections 3 and 4

respectively. The simulation results and discussion of these results are presented in sections 5 and 6 respectively, with the conclusion presented in section 7.

2. Implementation of a lab scale data acquisition system using the RSCAD GTNET card Phasor Measurement Units (PMUs)

The fundamental concepts governing the synchrophasor technology-based data acquisition and data transfer of power system economic dispatch problem solutions is explained in this section. The functions of the RTDS PMU-based system are shown in Fig. 1 below where the power system model is first simulated within the RSCAD software environment (orange box). The data from this model is firstly acquired (green box) from the simulation model, and then transferred to a remote end computer which is regarded as the power system control center, containing a database (red box) and also the optimisation algorithm solution (yellow box).

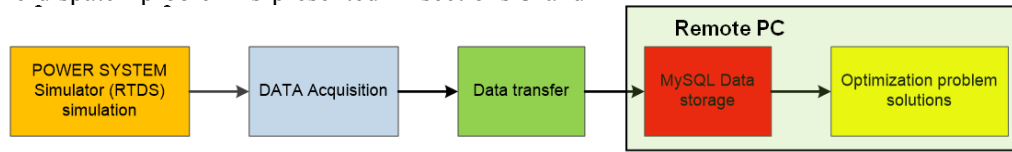


Fig.1: RTDS GTNET card PMU-based lab-scale systems functions

The block diagram in the figure above is expanded in the flow diagram in Fig. 2 below. The RSCAD simulation model outputs are transferred to the RTDS GTNET PMU card where the physical signal (Measurement) is transferred via Ethernet (Data transfer) and conforming to the IEEE-C37.118 standard. The PMU connection Tester software at the remote-end PC, verifies the integrity and quality of the transferred data signals from the virtual PMUs. The OpenPDC software represents a virtual Phasor Data Concentrator which combines signals from multiple Phasor Measurement Units (PMUs). The data from multiple PMUs is stored in a MySQL database (Data storage) on the same PC. The data from the database is read by the MATLAB algorithm that uses the Lagrange's method to solve the economic dispatch problem in real-time (Data optimisation problem solution). The block diagram shown in Fig. 3 which is an expanded view of both Figures 1 and 2, is that of the developed RTDS GTNET card PMU-based laboratory scale system to solve the economic dispatch problem in real-time, where

the RTDS generates the voltages and currents within the RSCAD software environment.

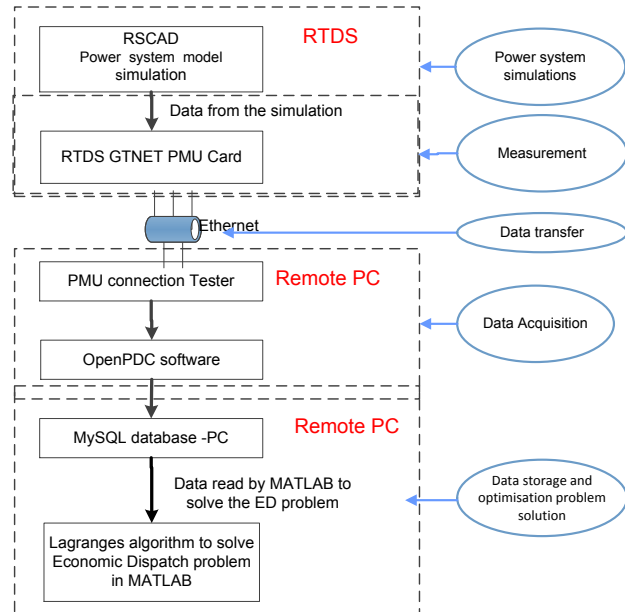


Fig.2: Flow diagram of the lab-scale data acquisition and data transfer system using the RTDS GTNET PMU technology to acquire and transfer data and to solve ED problem

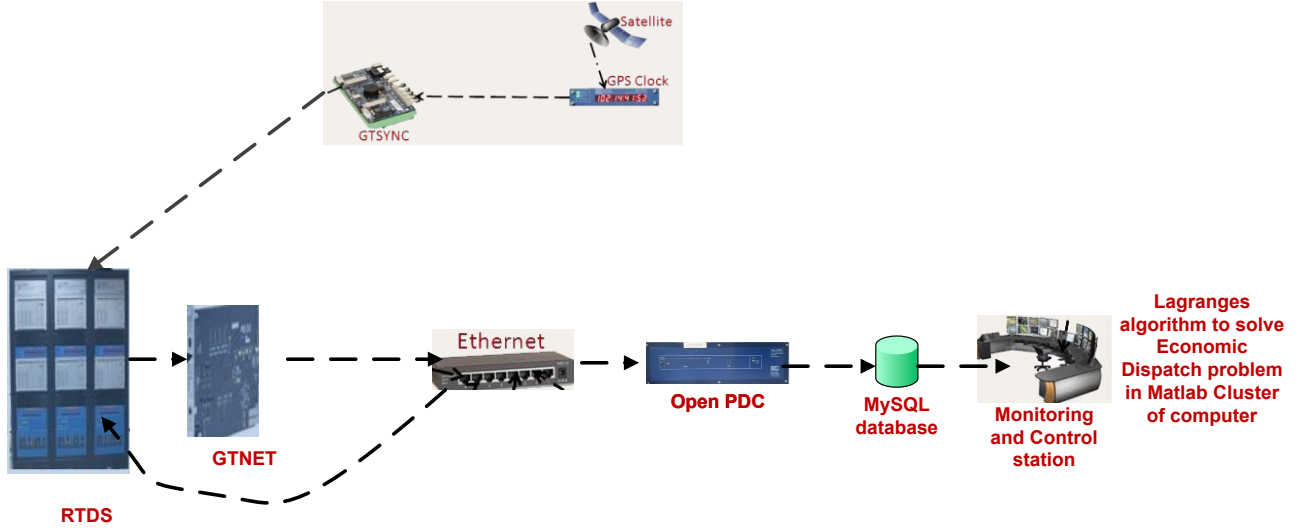


Fig. 3: Block diagram for the lab-scale data acquisition system based on the RTDS GTNET card PMU to solve the economic dispatch problem

These signals are then fed to the software-based PMUs (GTNET-PMUs). The measured data from the GTNET-PMU is transferred to the virtual Phasor Data Concentrator (PDC)-OpenPDC [4], using the Ethernet communication protocol. The GTNET card PMU used is configured within the RSCAD software environment and is synchronized to the Global Positioning System (GPS) using a SEL-2407 satellite clock with an antenna [15]. The RTDS GTNET PMU card allows for the use of a maximum of 8 independent PMUs to provide symmetrical component information related to the three-phase sets of voltages and currents, conforming to the IEEE-C37.118 standard, [8-9]. A single PMU can provide a total of 12 phasors (three-phase voltage and current magnitudes and phase angles), the measured frequency, the rate of change of frequency as well as four analogue values and a 1-to-16-bit digital value, [5-6]. The described RTDS output signals with the desired parameters are generated from within the RTDS using a GTNET card. From the GTNET card fixed in Rack-1 of the RTDS at the CSAEMS lab, voltage and current signals are sent to the remote end via Ethernet. At the remote end, the OpenPDC software [4] is used to capture the RTDS signals in real-time. These signals are archived in the MySQL database. Every five minutes, the data is retrieved from the MySQL database by the MATLAB [16] optimisation algorithm. The Lagrange's algorithm [13] is used to solve the Economic Dispatch (ED) problem using the real-time data which is retrieved from the MySQL database. The flow chart of

the algorithm for the real-time solution of the problem is given below in Fig. 4.

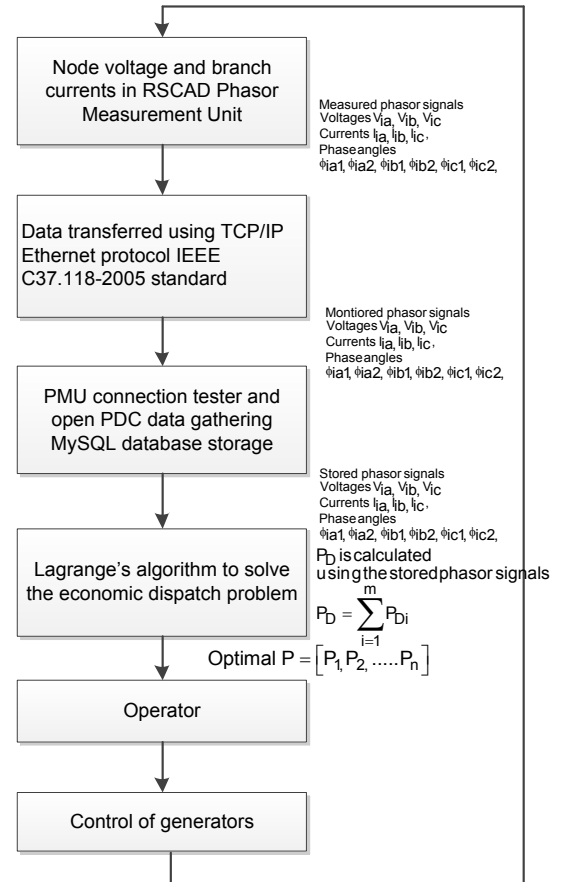


Fig. 4: Flow chart of the real-time solution of the dispatch problem using the GTNET card PMU-based data acquisition and transfer system

The paper considers only the real-time solution of the optimisation problem based on real-time acquired and transferred data and does not solve the problem for the control of the generators. The GTNET card PMU provides a user-defined action to select any number of PMUs from a maximum of eight available PMUs per GTNET card. This paper uses four PMUs based on the IEEE C37-118 standard [8] to transfer the three-phase current and voltage signals from the power system model simulation measurements at the remote end. Each PMU configuration has user-defined signal frame rates at either 50 or 60 Hz. The instrument transformer's (PTs and CTs) turns ratios are defined in the RSCAD GTNET card PMU AC source. Fig. 5 below shows the four PMUs with the user-defined input signal names for the three-phase voltage and current signals.

Name	Description	Value	Unit	Min	Max
rVT1	PMU1_Turns Ratio : 1	2000.0		1.0	10000.0
nVTA1	PMU1_A phase Input Signal Name	V2A			
nVTB1	PMU1_B phase Input Signal Name	V2B			
nVTC1	PMU1_C phase Input Signal Name	V2C			
rCT1	PMU1_Turns Ratio : 1	600.0		1.0	5000.0
nCTA1	PMU1_A phase Input Signal Name	I2A			
nCTB1	PMU1_B phase Input Signal Name	I2B			
nCTC1	PMU1_C phase Input Signal Name	I2C			
rVT2	PMU2_Turns Ratio : 1	2000.0		1.0	10000.0
nVTA2	PMU2_A phase Input Signal Name	V3A			
nVTB2	PMU2_B phase Input Signal Name	V3B			
nVTC2	PMU2_C phase Input Signal Name	V3C			
rCT2	PMU2_Turns Ratio : 1	600.0		1.0	5000.0
nCTA2	PMU2_A phase Input Signal Name	I3A			
nCTB2	PMU2_B phase Input Signal Name	I3B			
nCTC2	PMU2_C phase Input Signal Name	I3C			
rVT3	PMU3_Turns Ratio : 1	2000.0		1.0	10000.0
nVTA3	PMU3_A phase Input Signal Name	V4A			
nVTB3	PMU3_B phase Input Signal Name	V4B			
nVTC3	PMU3_C phase Input Signal Name	V4C			
rCT3	PMU3_Turns Ratio : 1	600.0		1.0	5000.0
nCTA3	PMU3_A phase Input Signal Name	I4A			
nCTB3	PMU3_B phase Input Signal Name	I4B			
nCTC3	PMU3_C phase Input Signal Name	I4C			
rVT4	PMU4_Turns Ratio : 1	2000.0		1.0	10000.0
nVTA4	PMU4_A phase Input Signal Name	V5A			
nVTB4	PMU4_B phase Input Signal Name	V5B			
nVTC4	PMU4_C phase Input Signal Name	V5C			
rCT4	PMU4_Turns Ratio : 1	600.0		1.0	5000.0
nCTA4	PMU4_A phase Input Signal Name	I5A			
nCTB4	PMU4_B phase Input Signal Name	I5B			
nCTC4	PMU4_C phase Input Signal Name	I5C			

Fig. 5: RSCAD GTNET PMU AC Source

The default turns ratio setting used in the PTs and CTs are 2000:1 and 600:1 turns respectively. Once the connection configuration is tested using the PMU connection tester, the corresponding configuration and connection files for each PMU are saved on the remote Personal-Computer (PC) where the OpenPDC software is running. This section presented the implementation of the lab-scale system. The next section presents the formulation of the dispatch problem.

3. Formulation of the dispatch problem

The objective function of the economic dispatch problem is to minimize the fuel cost or the emission criterion function of the thermal power plant as given in Equations (1) and (2) respectively.

Minimize

$$F_C = \sum_{i=1}^n F_i(P_i) = \sum_{i=1}^n (a_i P_i^2 + b_i P_i + c_i) [\$/hr] \quad (1)$$

Minimize

$$E_C = \sum_{i=1}^n E_i(P_i) = \sum_{i=1}^n (d_i P_i^2 + e_i P_i + f_i) [kg/hr] \quad (2)$$

Where:

F_C is the total Fuel Cost

E_C is the total emission value

$F_i(P_i)$ is the fuel cost of the i^{th} generator

$E_i(P_i)$ is the emission value of the i^{th} generator

P_i is the real power generation of unit i

a_i, b_i, c_i are the fuel cost coefficients of generating for unit i

d_i, e_i, f_i are the emission value coefficients of generating for unit i

n is the number of generating units

Under the constraints determined by the power balance, transmission loss, and generator limits, as given below.

1) Power balance constraint

$$\sum_{i=1}^n P_i = P_G = P_D + P_L [MW] \quad (3)$$

Where:

P_G is the total power generation of the system

P_D is the total demand of the system

P_L is the total transmission loss of the system

2) The transmission loss constraint can be expressed as

$$P_L = \sum_{i=1}^n \sum_{j=1}^n P_i B_{ij} P_j + \sum_{i=1}^n B_{0i} P_i + B_{00} [MW] \quad (4)$$

Where

B_{ij}, B_{0i}, B_{00} are the transmission loss coefficients

3) Generator operational constraints

$$P_{i,\min} \leq P_i \leq P_{i,\max}, i = \overline{1, n} \quad (5)$$

Where

$P_{i,\min}$ is the minimum value of the real power allowed to be produced by the generator i

$P_{i,\max}$ is the maximum value of the real power allowed to be produced by the generator i .

Two optimisation dispatch problems are formulated on the basis of the criteria (1) or (2) and the constraints given in Equations (3) to (5) as follows: Find the values of the active power P_i , $i = \overline{1, n}$ in such a way that the criteria Equations (1) or (2) are minimized under the constraints (3) to (5). The algorithm for solution of both optimisation dispatch problems are the same. They are described in the next section using the criterion given in Equation (1). This section presented the formulation of the economic dispatch problem. The following section describes the algorithm for the solution of the economic dispatch problem.

4. Algorithm for solution of the dispatch problem

A method for the Lagrange's solution of the economic dispatch optimisation problem Equation (1), subject to the constraints given in the Equations (3), (4) and (5) is developed on the basis of the function of Lagrange (L) by introduction of Lagrange's multiplier λ , [13].

$$L = \left[\sum_{i=1}^n [(a_i P_i^2 + b_i P_i + c_i)] + \lambda \left(P_D + \sum_{i=1}^n \sum_{j=1}^n P_i B_{ij} P_j + \sum_{i=1}^n B_{0i} P_i + B_{00} - \sum_{i=1}^n P_i \right) \right] \quad (6)$$

The optimisation problem in Equation (1), subject to the constraints given in Equations (3), (4) and (5) is transferred to the problem for minimization of L according to P_i , $i = \overline{1, n}$ and maximization of L according to λ , under the constraints given in Equation (5). The conditions for optimality are derived for the solution of the problem presented by Equations (5) and (6) as follows:

$$\text{According to } P_i, \quad \frac{\partial L}{\partial P_i} = 0, i = \overline{1, n} \quad (7)$$

$$\text{According to } \lambda, \quad \frac{\partial L}{\partial \lambda} = 0 \quad (8)$$

The derivation of the condition presented in Equation

(7) is as follows:

$$\frac{\partial L}{\partial P_i} = 2a_i P_i + b_i + \lambda \left(2 \sum_{j=1}^n B_{ij} P_j + B_{0i} - 1 \right) = 0, i = \overline{1, n} \quad (9)$$

Equation (5.9) can be written in a matrix-vector form as follows:

$$\begin{bmatrix} \frac{a_1}{\lambda} + B_{11} & B_{12} & B_{1n} \\ B_{21} & \frac{a_2}{\lambda} + B_{22} & B_{2n} \\ B_{n1} & B_{n2} & \frac{a_{1n}}{\lambda} + B_{nn} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 - \left(\frac{b_1}{\lambda} \right) - B_{01} \\ 1 - \left(\frac{b_1}{\lambda} \right) - B_{02} \\ \vdots \\ 1 - \left(\frac{b_1}{\lambda} \right) - B_{0n} \end{bmatrix} \quad (10)$$

If the value of the Lagrange's multiplier λ is known, Equation (10) can be solved according to the unknown vector P , using the MATLAB command:

$$P = E \setminus D \quad (11)$$

Where

$$E = \begin{bmatrix} 1 - \left(\frac{b_1}{\lambda} \right) - B_{01} \\ 1 - \left(\frac{b_1}{\lambda} \right) - B_{02} \\ \vdots \\ 1 - \left(\frac{b_1}{\lambda} \right) - B_{0n} \end{bmatrix} \text{ and } D = \begin{bmatrix} \frac{a_1}{\lambda} + B_{11} & B_{12} & B_{1n} \\ B_{21} & \frac{a_2}{\lambda} + B_{22} & B_{2n} \\ B_{n1} & B_{n2} & \frac{a_{1n}}{\lambda} + B_{nn} \end{bmatrix}$$

The value of λ is unknown and has to be calculated using the necessary condition for optimality as defined by Equation (11):

$$\frac{\partial L}{\partial \lambda} = \left(P_D + \sum_{i=1}^n \sum_{j=1}^n P_i B_{ij} P_j + \sum_{i=1}^n B_{0i} P_i + B_{00} - \sum_{i=1}^n P_i \right) = 0 = \Delta \lambda \quad (12)$$

Equation (12) is not a function of λ , but represents the gradient of L according to λ . At the optimal solution this gradient has to be equal to zero. An analytical solution for λ is not possible and a gradient procedure for calculation of λ is developed as follows:

$$\lambda^{(k+1)} = \lambda^k + \alpha \Delta \lambda^{(k)}, \lambda \neq 0 \quad (13)$$

Where $\Delta \lambda^{(k)}$ is determined by the equation (12), k is the index of the gradient procedure, and α is the step of the gradient procedure that starts with some given

initial value of the Lagrange's variable $\lambda^{(0)}$. When $\Delta\lambda = 0$, during the iterations the optimal solution optimal solution for the energy that has to be produced by the generators as a solution of Equation (10).

The obtained solutions for P_i , $i = \overline{1, n}$ have to belong to the constraint domain determined by Equation (5). That is why for every index k of the gradient procedure, the obtained solution is to fit to the constraint domain following the procedure:

$$P_i^{(k)} = \begin{cases} P_{i,\min}, & \text{if } P_i^{(k)} < P_{i,\min} \\ P_i^{(k)}, & \text{if } P_{i,\min} \leq P_i^{(k)} < P_{i,\max} \\ P_{i,\max}, & \text{if } P_i^{(k)} > P_{i,\max} \end{cases} \quad (14)$$

The condition for the end of the iterations is:

$$\Delta\lambda^{(k)} \leq \varepsilon, \text{ or } k = m \quad (15)$$

Where $\varepsilon > 0$ is a small number and m is the given maximum number of iterations.

The algorithm of the method is developed in [13], and is presented as follows:

- 1) The initial value of the Lagrange's multiplier is guessed: $\lambda^{(0)}$, and the value of the condition for optimality ε is given.
- 2) In Equation (10) matrix $E^{(0)}$ and $D^{(0)}$ are formed.
- 3) Equation (11) is solved and $P^{(0)} = E^{(0)} \setminus D^{(0)}$ is determined.
- 4) The obtained vector $P^{(0)}$ is fit to the constraint domain (14).
- 5) $\Delta\lambda^{(0)}$ is calculated using Equation (12) where $P^{(0)}$ is substituted.
- 6) The condition (15) is checked. If it is fulfilled the calculations stop, if not, improved value of $\lambda \rightarrow \lambda^{(1)}$ is calculated using Equation (13).
- 7) Calculations of the improved values of $P_i \rightarrow P_i^{(1)}$ are done as in Equation (14) and so on. Iterations continue until the condition (15) is satisfied or the maximum number of iterations is reached.
- 8) The optimal solution is used to calculate the total fuel cost and emission using Equation (1) and (2) respectively.

for the Lagrange's variable is obtained. It determines the

The flowchart of the algorithm for the optimisation solution is shown in Fig.6.

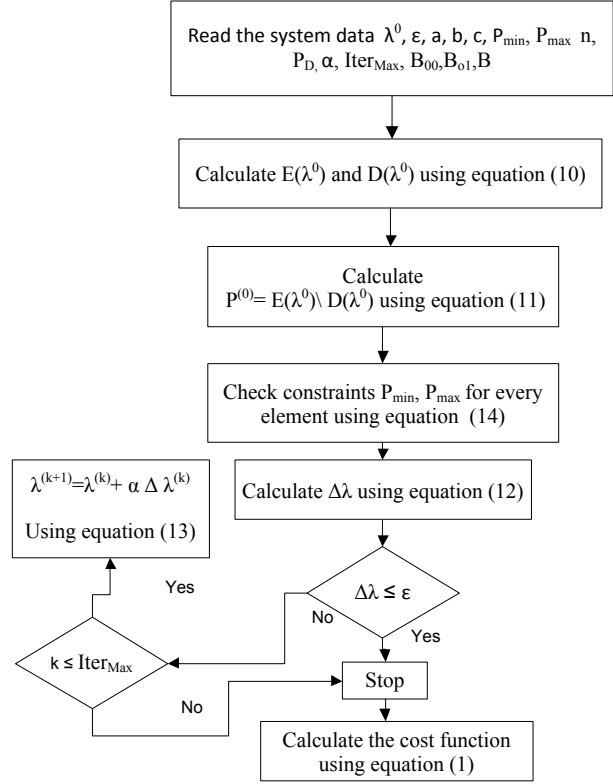


Fig.6: The flow chart of the economic dispatch problem solution algorithm using the Lagrange's method, [13]

This section presented the algorithm for the solution of the dispatch problem. The following section describes the model and presents the simulation results.

5. Power system model, simulation and assignment of the load demand powers to the GTNET card PMU and simulation results

The five-bus Indian power system model was designed and implemented within the RSCAD software environment as shown in Fig. 9 below. The five-bus power system has three constant source model generators (green boxes) and four loads components (yellow boxes) and their power demands are [20, 45, 40, 60] MWs. Currents entering into the four loads are monitored by connecting four circuit breakers (blue boxes) to the loads as is shown. The voltage signals of the loads are observed by monitoring the bus voltages at the points where the load terminals are connected.

The buses are interconnected with pi-type transmission lines (orange boxes). These voltage and current signals of the load components are assigned to the GTNET card and fourth loads are assigned to the PMU3 and PMU4 respectively. The monitored voltage and current signals are time-stamped by the GPS clock at the host end and are transferred to the remote-end PC using the Ethernet communication IEEE C37.118-2005 standard. The

PMU within the RSCAD software environment. The voltage and current phasor signals of the first two loads are assigned to PMU1 and PMU2, and the third RSCAD Runtime window for PMU 1 and PMU2 only, is shown in Fig.7 where the three-phase voltage and current magnitudes, the phase angles, and the real power values of the individual loads (power demands) are shown.

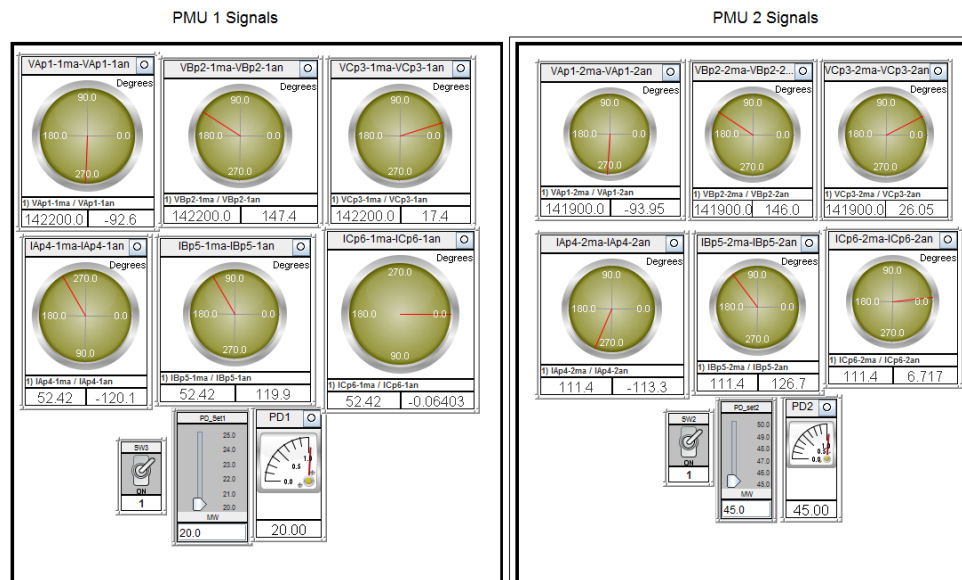


Fig. 7: Monitoring the voltage and current magnitudes and the phase angles of the PMU 1 and PMU 2 signals in the RSCAD software environment (Runtime Window)

The transferred signals are monitored in real-time at the remote end using the Open Phasor Data Concentrator (PDC) software. Fig.8 shows the RSCAD GTNET

voltage and current phasor signals together with their respective time stamps being monitored in the OpenPDC environment.

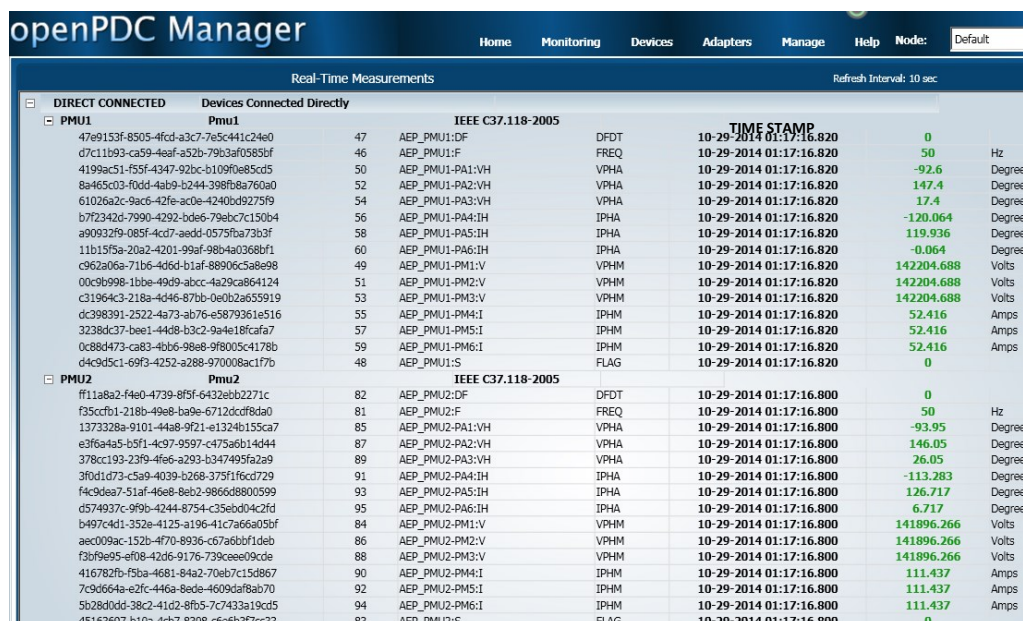


Fig.8: Monitoring the RSCAD GTNET card PMU 1 and PMU 2 signals in the OpenPDC environment

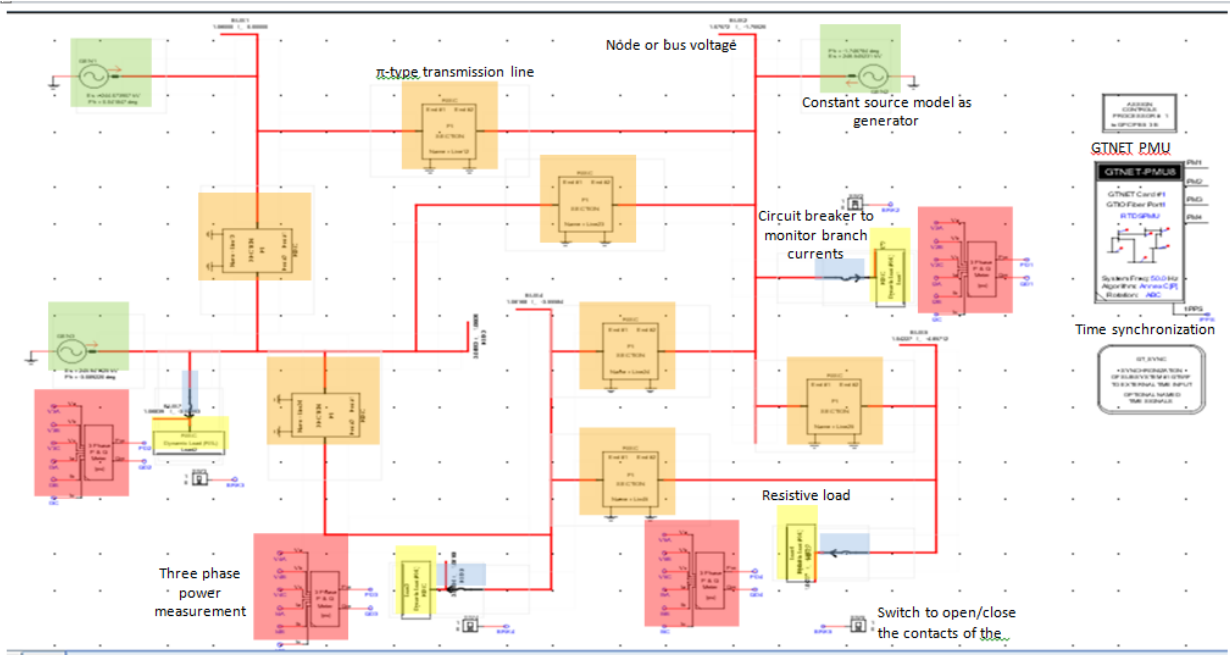


Fig.9: Five-bus power system network modelled in the RSCAD environment with additional components to implement data acquisition and data transfer using the GTNET card PMU signals

The OpenPDC data is stored in the MySQL database situated at the remote-end computer. The data is read by the optimisation dispatch algorithm in the MATLAB environment at the remote end computer every 5 minutes. The SQL query is used to select the particular signal from the MySQL database. The developed MATLAB software routine extracts the GTNET PMU signals from the MySQL database into the MATLAB

environment. Using these captured data signals the economic dispatch problem based on the Lagrange's algorithm is solved once every five minutes. Table 1 shows the PMU monitored three-phase voltage and current signals both in the RSCAD and in the MySQL environments for the initial loading condition of the power demand, $P_D = [20 \ 45 \ 40 \ 60]$ MW's respectively of the five-bus power system model.

Table 1: PMU signal monitored in the RSCAD and MySQL environment for the initial loading condition

PMU voltage and current signals		V_a	δ_{va}	V_b	δ_{vb}	V_c	δ_{vc}	I_a	δ_{Ia}	I_b	δ_{Ib}	I_c	δ_{Ic}	P_D
PMU #1 (P_{D1})	RSCAD environment	142200	-92.6	142200	147.4	142200	17.4	52.4	-120.1	52.4	119.9	52.4	-0.06	20.0
	MySQL environment	142200	-92.6	142200	147.4	142200	17.4	52.4	-120.1	52.4	119.9	52.4	-0.06	20.0
PMU #2 (P_{D2})	RSCAD environment	141900	-93.9	141900	146.0	141900	26.5	111.4	-113.0	111.4	126.7	111.4	6.7	45.0
	MySQL environment	141900	-93.9	141900	146.0	141900	26.5	111.4	-113.0	111.4	126.7	111.4	6.7	44.7
PMU #3 (P_{D3})	RSCAD environment	141100	-94.3	141100	145.6	141100	25.6	95.2	-102.4	95.2	137.6	95.2	17.6	40.0
	MySQL environment	141100	-94.3	141100	145.6	141100	25.6	95.2	-102.4	95.2	137.6	95.2	17.6	39.7
PMU #4 (P_{D4})	RSCAD environment	138600	-95.5	138600	144.5	138600	24.4	146.3	-105.9	146.3	134.1	146.3	14.2	60.0
	MySQL environment	138600	-95.5	138600	144.5	138600	24.4	146.3	-105.9	146.3	134.1	146.3	14.2	59.7

It is observed that PMU signals monitored in the RSCAD and the MySQL environments are very similar and hence it is assumed that the laboratory set-up

developed is capable of transferring the RTDS power system signals from the local to the remote end without any loss of data. The same procedure is repeated for

different loading conditions in order to test the data transfer capability of the developed lab-scale system. The different loading conditions used are:

$P_D = [20 \ 45 \ 40 \ 60]$ MW is the initial loading condition. The PMU signal for the initial loading is given in Table

1. The slider (P_{D1}) in the RSCAD run-time window is used to increase load one from 20 to 25 MW. Then the power demand becomes $P_D = [25 \ 45 \ 40 \ 60]$ MW and it is called the first loading condition. Table 2 displays the PMU signals monitored in both the RSCAD and MySQL environments for the first loading condition.

Table 2: PMU signals monitored in RSCAD and MySQL environment for the first loading condition

PMU voltage and current signals		V_a	δ_{va}	V_b	δ_{vb}	V_c	δ_{vc}	I_a	δ_{Ia}	I_b	δ_{Ib}	I_c	δ_{Ic}	PD
PMU #1 (PD1)	RSCAD environment	14200	-92.6	142200	147.4	142200	17.4	63.2	-115.3	63.2	124.7	63.2	4.6	25.0
	MySQL environment	14200	-92.6	142200	147.4	142200	17.4	63.2	-115.4	63.2	124.4	63.2	4.6	25.3
PMU #2 (PD2)	RSCAD environment	141900	-93.9	141900	146.0	141900	26.5	111.4	-113.0	111.4	126.7	111.4	6.7	45.0
	MySQL environment	141900	-93.9	141900	146.0	141900	26.5	111.4	-113.5	111.4	126.6	111.4	6.5	44.7
PMU #3 (PD3)	RSCAD environment	141100	-94.3	141100.0	145.6	141100	25.6	95.2	-102.4	95.2	137.6	95.2	17.6	40.0
	MySQL environment	141100	-94.3	141100.0	145.6	141100	25.6	95.2	-102.4	95.2	137.6	95.2	17.6	39.6
PMU #4 (PD4)	RSCAD environment	138600	-95.5	138600	144.5	138600	24.4	146.3	-105.9	146.3	134.1	146.3	14.2	60.0
	MySQL environment	138600	-95.5	138600	144.5	138600	24.4	146.3	-105.9	146.3	134.1	146.3	14.2	59.7

The slider (P_{D2}) in the RSCAD run-time window is used to increase the load two from 45 to 50 MW. Then the power demand becomes $P_D = [25 \ 50 \ 40 \ 60]$ MW and

it is called the second loading condition. Table 3 shows the PMU signals monitored in both the RSCAD and the MySQL environments for the second loading condition.

Table 3: PMU signals monitored in the RSCAD and MySQL environment for the second loading condition

PMU voltage and current signals		V_a	δ_{va}	V_b	δ_{vb}	V_c	δ_{vc}	I_a	δ_{Ia}	I_b	δ_{Ib}	I_c	δ_{Ic}	PD
PMU #1 (PD1)	RSCAD environment	142200	-92.6	142200	147.4	142200	17.4	63.2	-115.3	63.2	124.7	63.2	4.6	25.0
	MySQL environment	142200	-92.6	142200	147.4	142200	17.4	63.2	-115.3	63.2	124.7	63.2	4.6	24.7
PMU #2 (PD2)	RSCAD environment	141900	-93.95	141900	146.0	141900	26.5	122.6	-115.5	122.6	128.5	122.6	8.4	50.0
	MySQL environment	141900	-93.95	141900	146.0	141900	26.5	122.6	-115.5	122.6	128.5	122.6	8.4	49.5
PMU #3 (PD3)	RSCAD environment	141100.0	-94.37	141100.0	145.6	141100.0	25.63	95.25	-102.4	95.25	137.6	95.25	17.6	40.0
	MySQL environment	141100.0	-94.37	141100.0	145.6	141100.0	25.63	95.25	-102.4	95.25	137.6	95.25	17.6	39.7
PMU #4 (PD4)	RSCAD environment	138600	-95.52	138600	144.5	138600	24.48	146.3	-105.9	146.3	134.1	146.3	14.2	60.0
	MySQL environment	138600	-95.52	138600	144.5	138600	24.48	146.3	-105.9	146.3	134.1	146.3	14.2	59.8

The slider (P_{D3}) in the RSCAD run-time window is used to increase the load three from 40 to 45 MW. Then the power demand becomes $P_D = [25 \ 50 \ 45 \ 60]$ MW and

it is called the third loading condition. Table 4 displays the PMU signals monitored in both the RSCAD and the MySQL environments for the third loading condition.

Table 4: PMU signals monitored in the RSCAD and MySQL environment for the third loading condition

PMU voltage and current signals		V_a	δ_{va}	V_b	δ_{vb}	V_c	δ_{vc}	I_a	δ_{ia}	I_b	δ_{ib}	I_c	δ_{ic}	PD
PMU #1 (PD1)	RSCAD environment	142200	-92.6	142200	147.4	142200	17.4	63.2	-115.3	63.2	124.7	63.2	4.7	25.0
	MySQL environment	142200	-92.6	142200	147.4	142200	17.4	63.2	-115.3	63.2	124.7	63.2	4.6	24.7
PMU #2 (PD2)	RSCAD environment	141900	-93.9	141900	146.0	141900	26.5	122.6	-115.5	122.6	128.5	122.6	8.4	50.0
	MySQL environment	141900	-93.9	141900	146.0	141900	26.5	122.6	-115.5	122.6	128.5	122.6	8.4	49.5
PMU #3 (PD3)	RSCAD environment	141000	-94.4	141000	145.6	141000	25.56	107.0	-101.7	107.0	138.3	107.0	18.3	45.0
	MySQL environment	141000	-94.4	141000	145.6	141000	25.56	107.0	-101.7	107.0	138.3	107.0	18.3	44.7
PMU #4 (PD4)	RSCAD environment	138600	-95.5	138600	144.5	138600	24.48	146.3	-105.9	146.3	134.1	146.3	14.1	60.0
	MySQL environment	138600	-95.5	138600	144.5	138600	24.48	146.3	-105.9	146.3	134.1	146.3	14.1	59.5

The slider (P_{D4}) in the RSCAD run-time window is used to increase load four from 60 to 65 MW. Then the power demand becomes $P_D = [25 \ 50 \ 45 \ 65]$ MW and it is called

the fourth loading condition. Table 5 shows the PMU signals monitored in both the RSCAD and the MySQL environments for the fourth loading condition.

Table 5: PMU signals monitored in the RSCAD and MySQL environment for the fourth loading condition

Voltage and current signals		V_a	δ_{va}	V_b	δ_{vb}	V_c	δ_{vc}	I_a	δ_{ia}	I_b	δ_{ib}	I_c	δ_{ic}	PD
PMU #1 (PD1)	RSCAD environment	142200	-92.6	142200	147.4	142200	17.4	63.2	-115.3	63.2	124.7	63.2	4.7	25.0
	MySQL environment	142200	-92.6	142200	147.4	142200	17.4	63.2	-115.3	63.2	124.7	63.2	4.6	24.750
PMU #2 (PD2)	RSCAD environment	141900	-93.9	141900	146.0	141900	26.5	122.6	-115.5	122.6	128.5	122.6	8.4	50.0
	MySQL environment	141900	-93.9	141900	146.0	141900	26.5	122.6	-115.5	122.6	128.5	122.6	8.4	49.5
PMU #3 (PD3)	RSCAD environment	141000	-94.4	141000	145.6	141000	25.56	107.0	-101.7	107.0	138.3	107.0	18.3	45.0
	MySQL environment	141000	-94.4	141000	145.6	141000	25.56	107.0	-101.7	107.0	138.3	107.0	18.3	44.7
PMU #4 (PD4)	RSCAD environment	138400	-95.7	138400	144.2	138400	24.24	158.4	-105.4	158.4	134.6	158.4	14.6	65.0
	MySQL environment	138400	-95.7	138400	144.2	138400	24.24	158.4	-105.4	158.4	134.6	158.4	14.6	64.9

The monitored PMU voltage, current, and phase angle signals are used to calculate the real power of the loads using Equation (16). The voltage and current data are stored in the MySQL database; they are then read by the MATLAB-based optimisation algorithm where the real power of the load components is calculated using the data phasor signals acquired at the remote end using Equation (16).

$$P_D = \sum_{i=1}^m \left[V_{ia} I_{ia} \cos(\Phi_{ia1} - \Phi_{ia2}) + V_{ib} I_{ib} \cos(\Phi_{ib1} - \Phi_{ib2}) + V_{ic} I_{ic} \cos(\Phi_{ic1} - \Phi_{ic2}) \right] \quad (16)$$

Where

P_D is the total power demand in Watts

V_{ia}, V_{ib}, V_{ic} are bus voltage magnitudes in volt for the i^{th} load, $i = \overline{1, m}$

I_{ia}, I_{ib}, I_{ic} are branch currents in Amps for the i^{th} load, $i = \overline{1, m}$

Φ_{ia1}, Φ_{ia2} are phase angle between the voltage and current in phase A for the i^{th} load, $i = \overline{1, m}$

Φ_{ib1}, Φ_{ib2} are phase angle between the voltage and current in phase B for the i^{th} load, $i = \overline{1, m}$

Φ_{ic1}, Φ_{ic2} are phase angle between the voltage and current in phase C for the i^{th} load, $i = \overline{1, m}$

A comparison of the measured RSCAD load power demands with the power demands calculated using the transferred GTNET card PMU signals and the OpenPDC software is given in Table 6. It is observed that the signal from the RSCAD environment, conforming to the IEEE C37.118-2005 standard is successfully transferred to the remote end (MySQL database) using the GTNET card PMU-based system and the OpenPDC software, without any data loss. It

can therefore be concluded that the implemented laboratory setup for the power system data acquisition and data transfer is operating according to the requirements and the data measurements have been validated. This method of data acquisition and data transfer can be used by the control centers in the monitoring and control of the power grid in order to solve the energy optimisation dispatch problem in real-time.

Table 6: Comparison of the measured load power demands in the RSCAD with the power demands calculated using the GTNET card PMU signals and OpenPDC software

PMU #1 (P_{D1}) MW		PMU #2 (P_{D2}) MW		PMU #3 (P_{D3}) MW		PMU #4 (P_{D4}) MW	
RSCAD	PMU 1	RSCAD	PMU 2	RSCAD	PMU 3	RSCAD	PMU 4
20	19.84	45	44.76	40	39.91	60	59.84
25	24.84	45	44.76	40	39.91	60	59.84
25	24.84	50	49.76	40	39.91	60	59.84
25	24.84	50	49.76	45	44.91	60	59.84
25	24.84	50	49.76	45	44.91	65	64.84

The Economic dispatch solution using the RTDS GTNET card PMU data acquisition and data transfer system is given in Table 7. The total power demand varies from 165

to 185 MW with an increment of 5 MWs. It is observed that the fuel cost increases with the increase in the power demand.

Table 7: Economic dispatch problem solution using the GTNET card PMU signals

P _D in M W	Generator real powers in MW						P _L in MW	Lagrange's algorithm		Fuel cost in Rs/hr	
	P ₁		P ₂		P ₃			Number of iterations (optimal)	Computation time in sec (Optimal)		
	MATLAB (Optimal)	RSCAD (Simulation)	MATLAB (Optimal)	RSCAD (Simulation)	MATLAB (Optimal)	RSCAD (Simulation)				MATLAB (Lagrange's)	RSCAD (Newton Raphson)
165	55.40	46.11	55.89	68.79	59.96	52.23	6.79	520	1.029	695.5	703.5
170	56.90	51.19	57.76	69.98	61.97	52.09	7.18	523	1.022	709.7	723.35
175	58.40	56.35	59.35	68.79	63.98	52.23	7.57	525	1.107	723.6	737.27
180	59.89	61.53	61.54	68.94	66.00	52.26	7.98	527	1.19	737.8	751.35
185	61.37	66.89	63.44	68.89	68.03	52.20	8.39	529	1.63	752.2	765.58

The Lagrange's method can be used to provide optimal set points for the generator power production. The load flow solution within the RSCAD software environment uses the Newton-Raphson numerical method. By solving the power flow problem the real power of the three generators are known and are used to calculate the

fuel cost (on the far right) of the power system which is shown in Figure 10 for the case of $P_D=165$ MW. Also from Table 7 it can be seen that the fuel cost is lower using the Lagrange's method when compared to the results obtained by the RSCAD simulation.

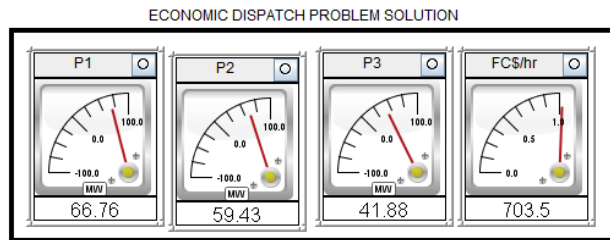


Figure 10: Economic dispatch problem solution in the RSCAD software environment for a power demand of 165 MW

The comparison of the solution of the dispatch problem using the developed two lab-scale systems is given in Table 9. The table contains a comparison for power demand, load power, the number of iterations, computation time, and the software platform used to perform the calculation. The highlighted boxes indicate the comparison for the Fuel cost in Rupees per hour, where firstly the calculation is performed in MATLAB

with the signal taken from the GTNET card PMU output (blue box), and secondly the calculation in MATLAB is performed with the output taken from the front panel analog output PB5 processor card (red box). It is observed that the values for the fuel cost are very similar although the physical signals are taken from two different outputs from within the RTDS simulation model.

Table 9: Comparison of the economic dispatch problem solutions using the signals taken from the RTDS GTNET card PMU and the front panel analog output RTDS PB5 card signals

P_D in MW	Synchrophasor Technology using GTNET card PMU signals					RTDS PB5 card front panel analog output signals					
	P_L in MW	Lagrange's method		Fuel cost in Rs/hr		P_D in MW	P_L in MW	Number of iterations	Computation time in sec	Fuel cost in Rs/hr	
		Number of iterations	Computation time in sec	MATLAB	RSCAD					MATLAB	RSCAD
165	6.79	520	1.029	695.5	709.23	165	4.80	701	1.27	695.7	709.60
170	7.18	523	1.022	709.7	723.35	170	5.10	703	1.25	709.60	723.40
175	7.57	525	1.107	723.6	737.27	175	5.40	705	1.34	722.40	737.28
180	7.98	527	1.19	737.8	751.35	180	5.71	706	1.41	735.70	751.42
185	8.39	529	1.63	752.2	765.58	185	6.03	708	1.26	749.50	765.65

This section presented the power system model, the simulation thereof, the assignment of the load demand powers to the GTNET card PMU and the simulation results. The following section describes a brief discussion on the data acquisition and transfer systems using the GTNET card PMU signals.

6. Discussion on the operating characteristics of the data acquisition and data transfer systems using the GTNET card PMU signals

This paper describes the application of data acquisition and data transfer using the RTDS GTNET card PMU signals in order to solve dispatch optimisation problems at the remote end control centre PC. The five-bus Indian utility power system model is used to validate the data transfer capability. Four different loading conditions are used to validate the data transfer capability of the developed lab-scale systems.

The following conclusions can be made:

- The GTNET card PMU supports the IEEE C37.118-2005 standard to transfer the large, complex power system network data from the local to the remote end in real-time.
- The data transfer capability of the synchrophasor technology using the RTDS GTNET card PMU is very fast and accurate. The loss of data during the process of communication and signal transformations is very small.

- The comparison of the economic dispatch problem solution at both the local and remote end is done. It has been proven that the economic dispatch solution using the Lagrange's method provides accurate values for real power that is to be produced by the generators, and the fuel costs are reduced using the outputs from the GTNET PMU.

7. Conclusion

This paper investigates the capabilities of the developed data acquisition and data transfer systems based on the RTDS GTNET card PMU-based signals to provide real-time data for the solution of a dispatch optimisation problem. The investigations are presented for the five-bus Indian power system model using different power demands. It is proven that the synchrophasor technology is an ideal solution for data acquisition and data transfer between the host and the remote PCs without any data loss. The optimized real power of the generators can be transmitted back to the RTDS models in RSCAD as set-points for the generators in the RSCAD simulation model. The GTNET card PMU-based data acquisition and data transfer systems creates favourable conditions for the optimisation algorithm to produce a better solution. The developed lab-scale systems will play a vital role in the future developments of a smart grid energy management system. The paper provides the results of

the developed data acquisition and data transfer systems to solve the economic dispatch problem in real-time using the real-time data.

Acknowledgement

The authors gratefully acknowledge the support and for the use of the equipment and facilities within the Center for Substation Automation and Energy Management Systems at the Electrical Engineering Department of the Cape Peninsula University of Technology, South Africa to carry out this research work. This research work is funded by the National research foundation (NRF) THRIP grant TP2011061100004 and ESKOM TESP for “CSAEMS development and growth”.

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