# PMU-based solution for the economic dispatch problem using the Real Time Digital Simulator

## RTDS User Conference

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# Background

- 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 current SCADA system does not allow for the fast data acquisition and processing of information for the implementation of 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 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 and is represented by their magnitude, active and reactive power only.
  - The measurement window is large, which produces data that is not as accurate with the system changes. The assumption is that during the measurement window period the power system parameters will change and that the system will remain constant.

# Background …

- The SCADA system does not allow measurement of the power system voltage and current phase 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.
- Based on this data a real-time situational awareness is created and makes it possible to implement fast real-time control.
- Online monitoring of the currently large interconnected power system is important to visualize the network in real-time, which has become possible with the advent of the synchrophasor technology.

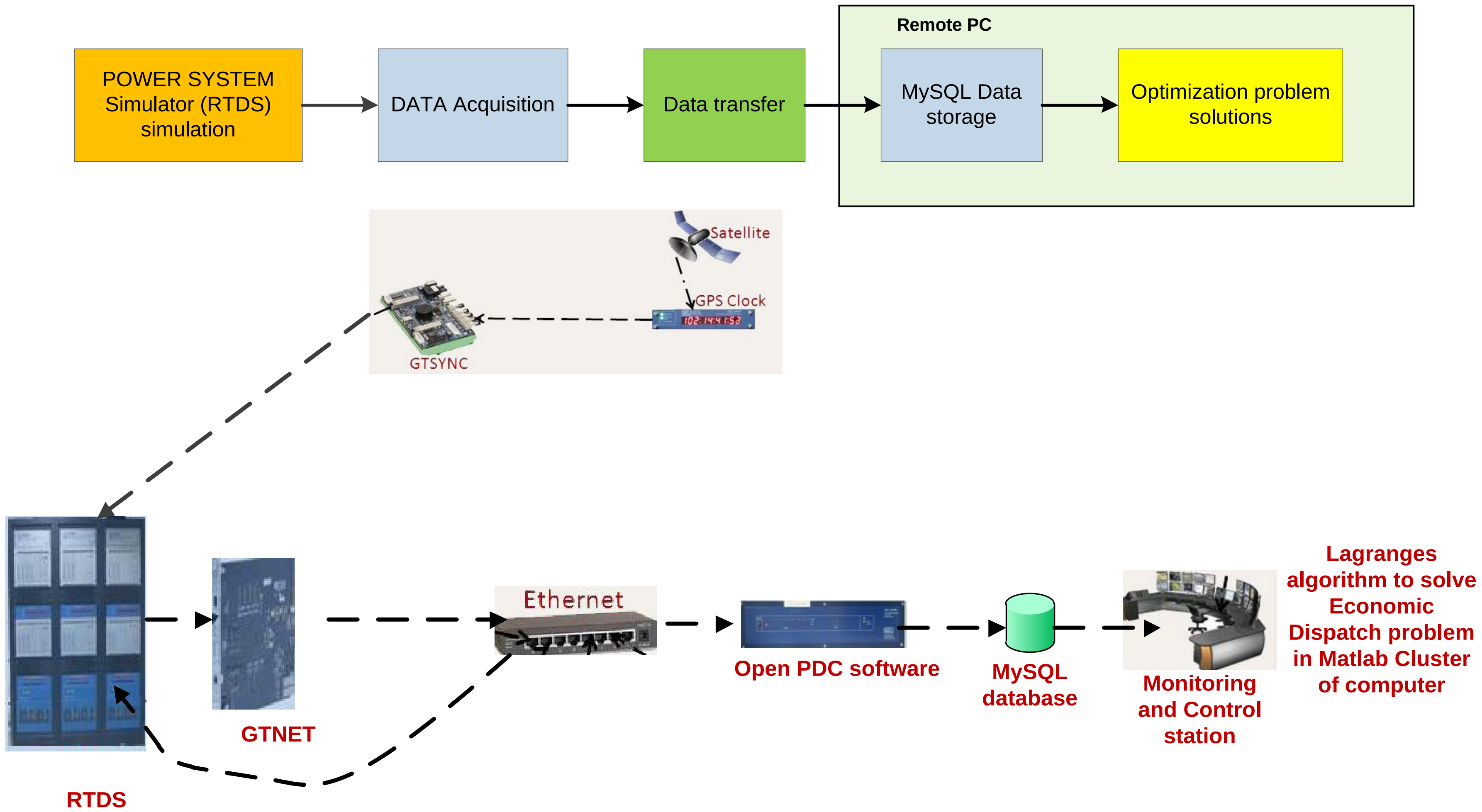
# Introduction

- 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
  i. Power systems are expected to operate close to the maximum capacity
  ii. 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.

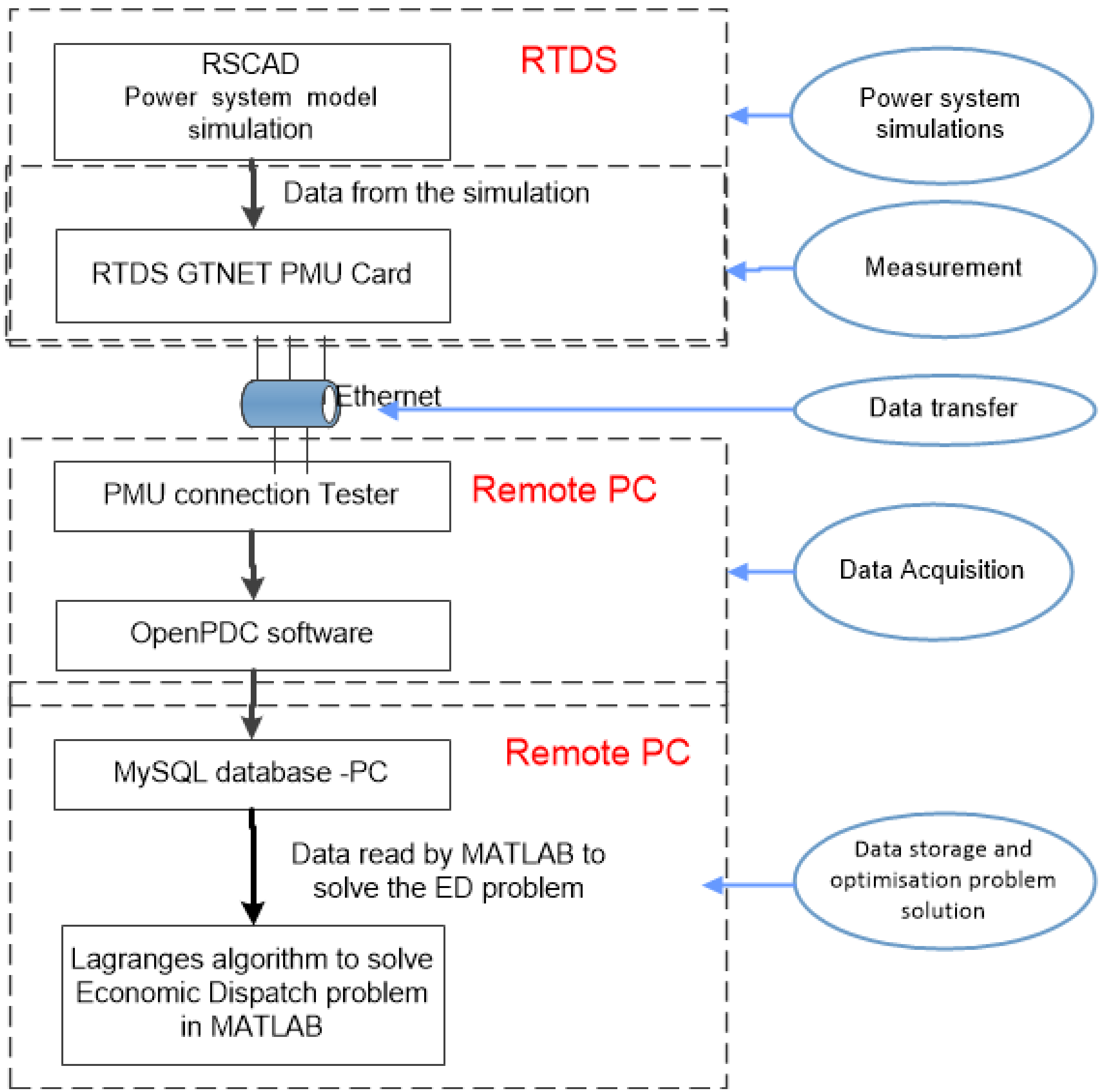
# Introduction …

- 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 the power system energy management problem.
- Data measurement and acquisition, data transfer and distribution through a communication network, and data storage and retrieval is incorporated 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
- 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 is performed.

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



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



# Lab-scale data acquisition system cont…

- The RTDS generates the voltages and currents within the RSCAD software environment.
- 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 software, 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.
- At the remote end, the OpenPDC software 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 optimisation algorithm.
- The Lagrange's algorithm developed by (Krishnamurthy and Tzoneva, 2013) is used to solve the Economic Dispatch (ED) problem using the real-time data which is retrieved from the MySQL database.

# Economic Dispatch

## What is economic dispatch?

- The operation of generation facilities to produce energy at the lowest cost to reliably serve consumers and recognizing any operational limits of generation

## Frequency of the dispatch

Performing an economic dispatch solution more frequently (e.g., 5 or 15 minutes rather than each hour) affects the level of costs

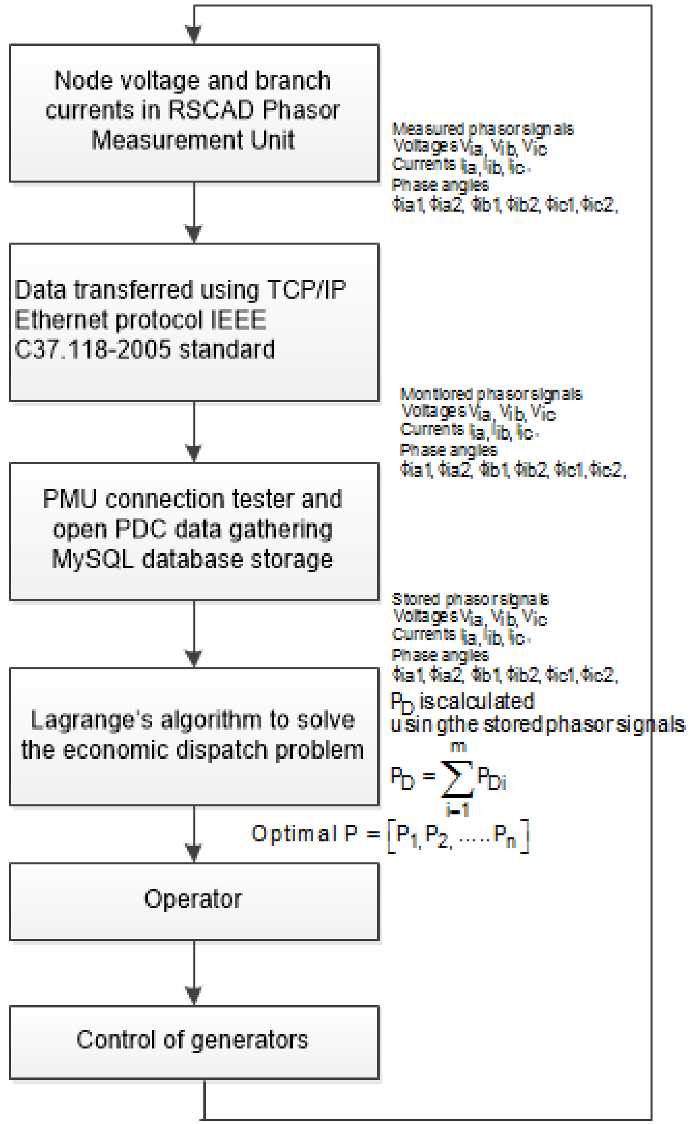
## Communication of information

- Generation operators, transmission owners, and load serving entities must provide accurate and current information for planning and dispatch functions
- Inadequate or incomplete communications affects the level of costs of the economic dispatch.

## Software tools for dispatch and information

- Reliable and secure computer software is essential for rapidly responding to system changes.
- To maintain power system reliability and selecting the lowest cost generators to dispatch.

# Real-time solution of the dispatch problem using the GTNET card PMU-based data acquisition and transfer system



# Optimisation

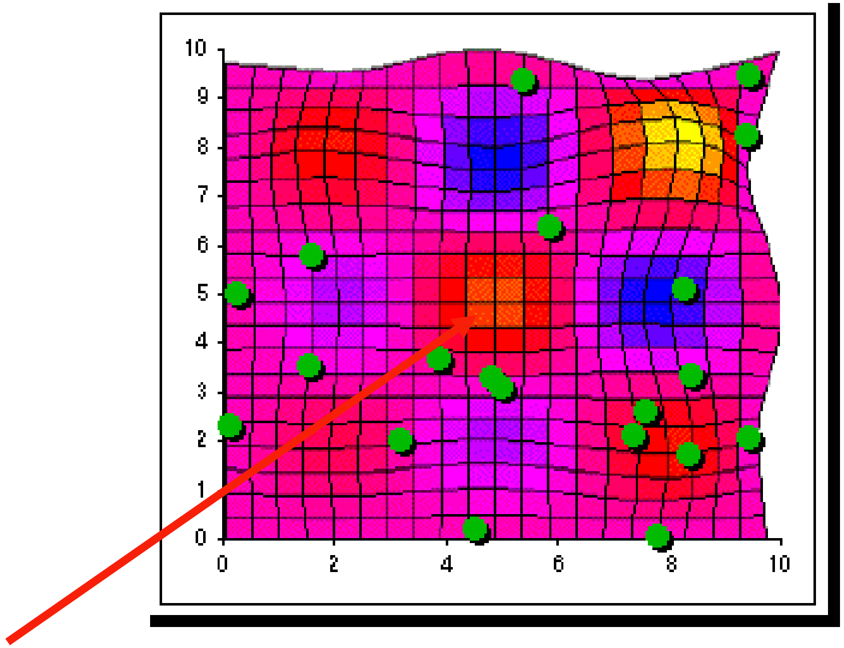
## Define Optimisation

Optimization is a mathematical discipline that concerns finding either a minimum or maximum of functions, subject to the constraints.

## Classical method

A mathematical approach used to find the unknown vectors through the derivative of the objective function with respect to the constraints.

| Most used Classical methods |
| --- |
| Dynamic Programming |
| Linear Programming |
| Recursive algorithm |
| Interior point method |
| Benson's algorithm |
| Lagrange's<br>Joseph-Louis Lagrange |




**Animated illustration**

# Formulation of the economic dispatch problem

The objective is to minimize the CEED fuel cost equation subject to the constraints and is expressed as,

$$F_T = \sum_{i=1}^{n}\left[(a_i P_i^2 + b_i P_i + c_i) + h_i\left(d_i P_i^2 + e_i P_i + f_i\right)\right] \text{ [\$/hr]} \quad (1)$$

Under the constraints

1) Power balance constraint

$$\sum_{i=1}^{n} P_i = P_G = P_D + P_L \text{ [MW]} \quad (2)$$

2) Generator operational constraints

$$P_{i,\min} \le P_i \le P_{i,\max}, i = \overline{1,n} \text{ [MW]} \quad (3)$$

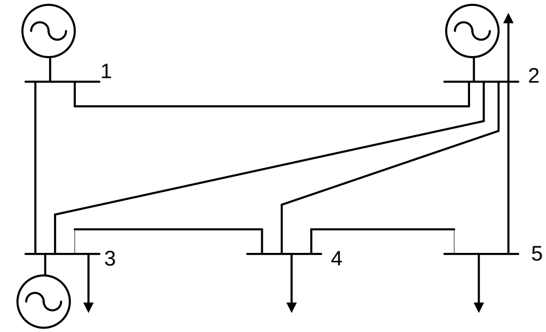



**Fig: Single line diagram of the five bus power system model**

- Number of generators are 3
- Number of Transmission lines are 7
- Number of Loads are 4

# Combined Economic Emission Dispatch (CEED) Problem using Lagrange's algorithm

Function of Lagrange is formulated by introduction of the Lagrange's multiplier λ , as follows:

$$L = \left[ \sum_{i=1}^{n} \left[ (a_i P_i^2 + b_i P_i + c_i) + h_i \left( d_i P_i^2 + e_i P_i + f_i \right) \right] + \lambda \left( P_D + \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} - \sum_{i=1}^{n} P_i \right) \right] \qquad (4)$$

Necessary conditions for optimality for solution of the problem (4)

i.e: According to $P_i$, $\frac{\partial L}{\partial P_i} = 0, i = \overline{1,n}$ (5)

Derivation of the condition (5) is as follows:

$$\frac{\partial L}{\partial P_i} = 2a_i P_i + b_i + h_i \left( 2d_i P_i + e_i \right) + \lambda \left( 2\sum_{j=1}^{n} B_{ij} P_j + B_{0i} - 1 \right) = 0, i = \overline{1,n} \qquad (6)$$

P=E\D (7)

Where

$$E = \begin{bmatrix} \frac{a_1 + h_1 d_1}{\lambda} + B_{11} & B_{12} & B_{1n} \\ B_{21} & \frac{a_2 + h_2 d_2}{\lambda} + B_{22} & B_{2n} \\ B_{n1} & B_{n2} & \frac{a_{1n} + h_n d_n}{\lambda} + B_{nn} \end{bmatrix}, \quad D = \frac{1}{2} \begin{bmatrix} 1 - \left( \frac{b_1 + h_1 e_1}{\lambda} \right) - B_{01} \\ 1 - \left( \frac{b_1 + h_1 e_1}{\lambda} \right) - B_{02} \\ 1 - \left( \frac{b_1 + h_1 e_1}{\lambda} \right) - B_{0n} \end{bmatrix}, \quad P = \left[ P_1 \;\; P_2 \;\; P_3 \;\; \cdots P_n \right]^T \qquad (8)$$

# Lagrange's method for CEED Problem

The condition for optimality, $\frac{\partial L}{\partial \lambda} = 0$

$$\frac{\partial L}{\partial \lambda} = \left( P_D + \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} - \sum_{i=1}^{n} P_i = 0 = \Delta\lambda \right) \quad (9)$$

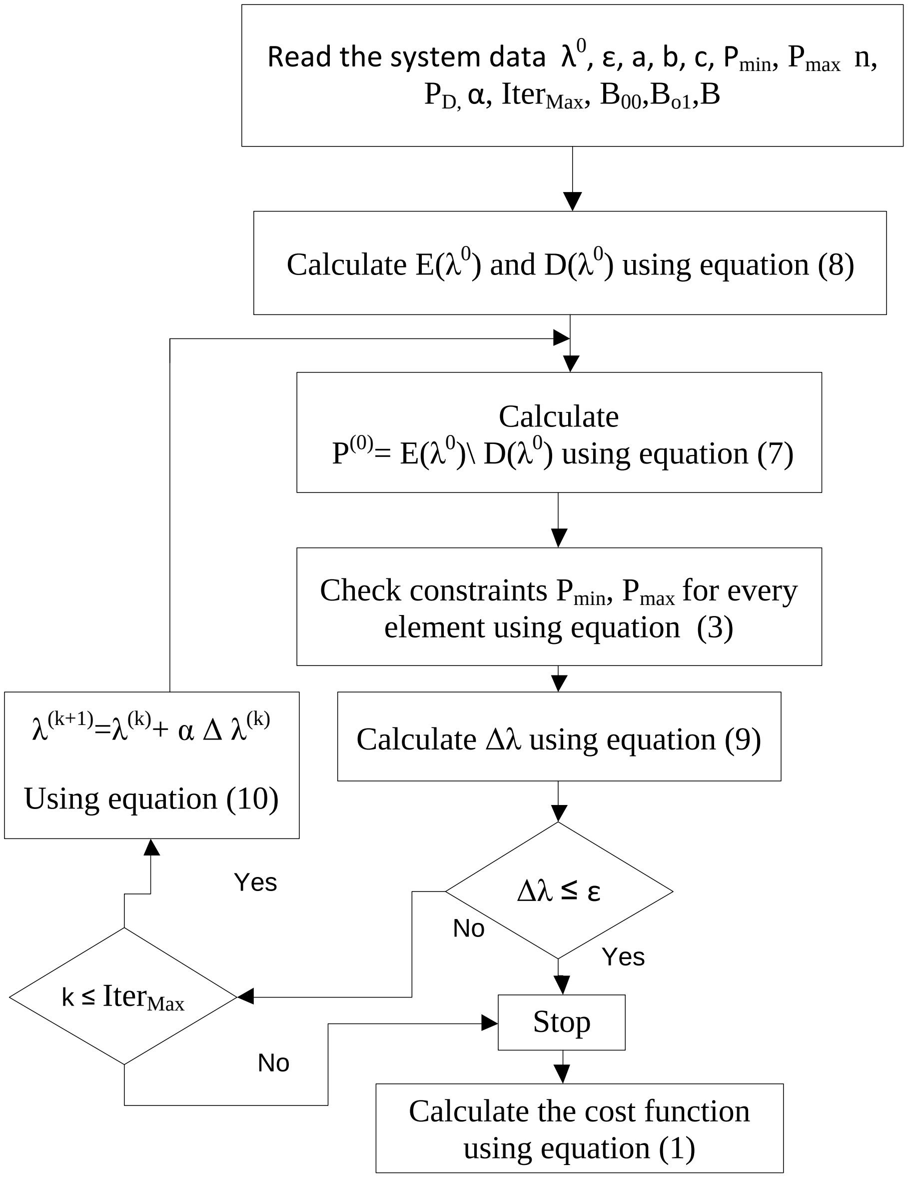
The gradient procedure for calculation of λ has to be developed as follows:

$$\lambda^{(k+1)} = \lambda^k + \alpha \Delta\lambda^{(k)}, \lambda \neq 0 \quad (10)$$

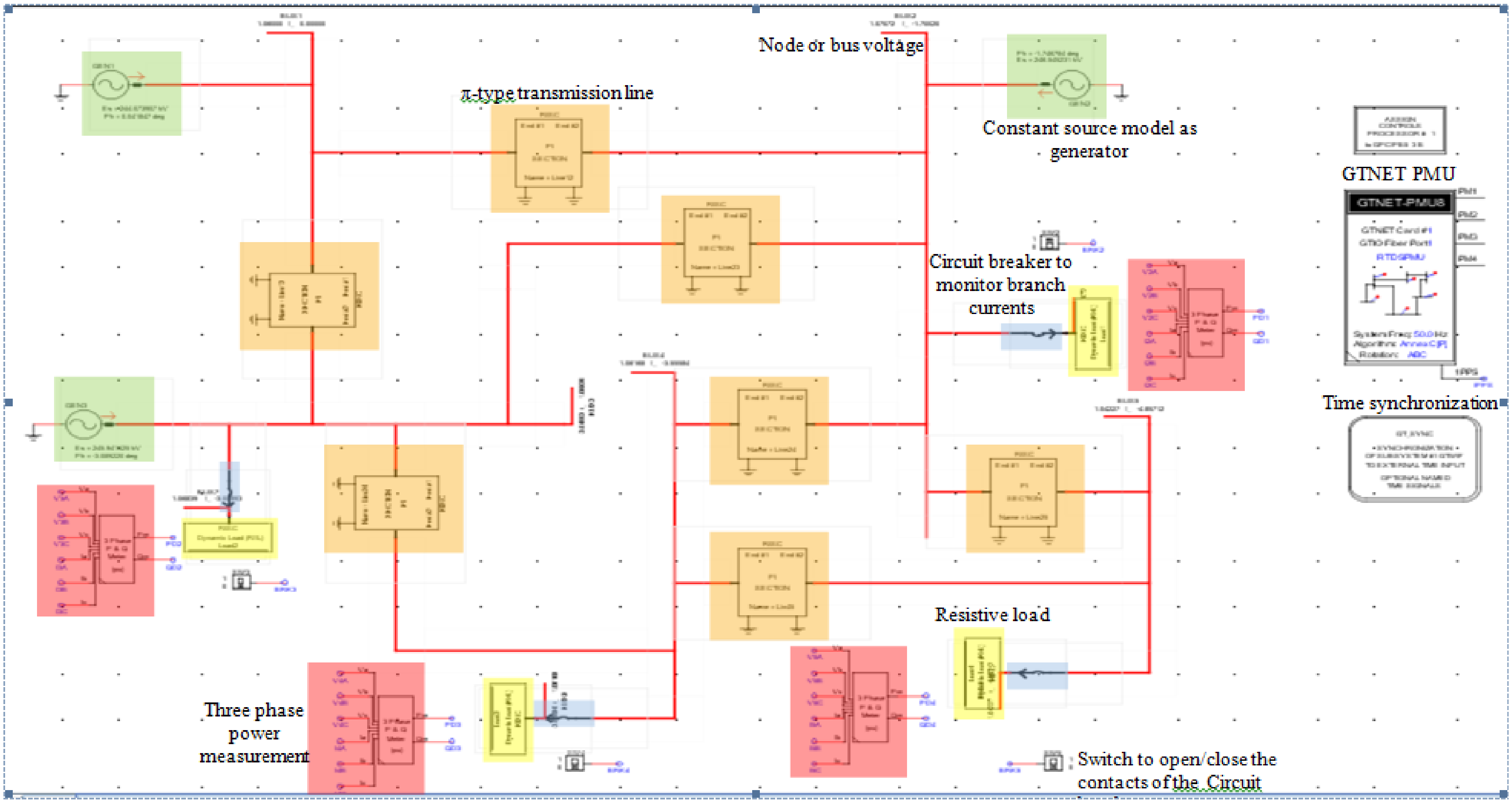
The condition for end of the iterations is

$\Delta\lambda^{(k)} \leq \varepsilon$, or $k = m$ (11)

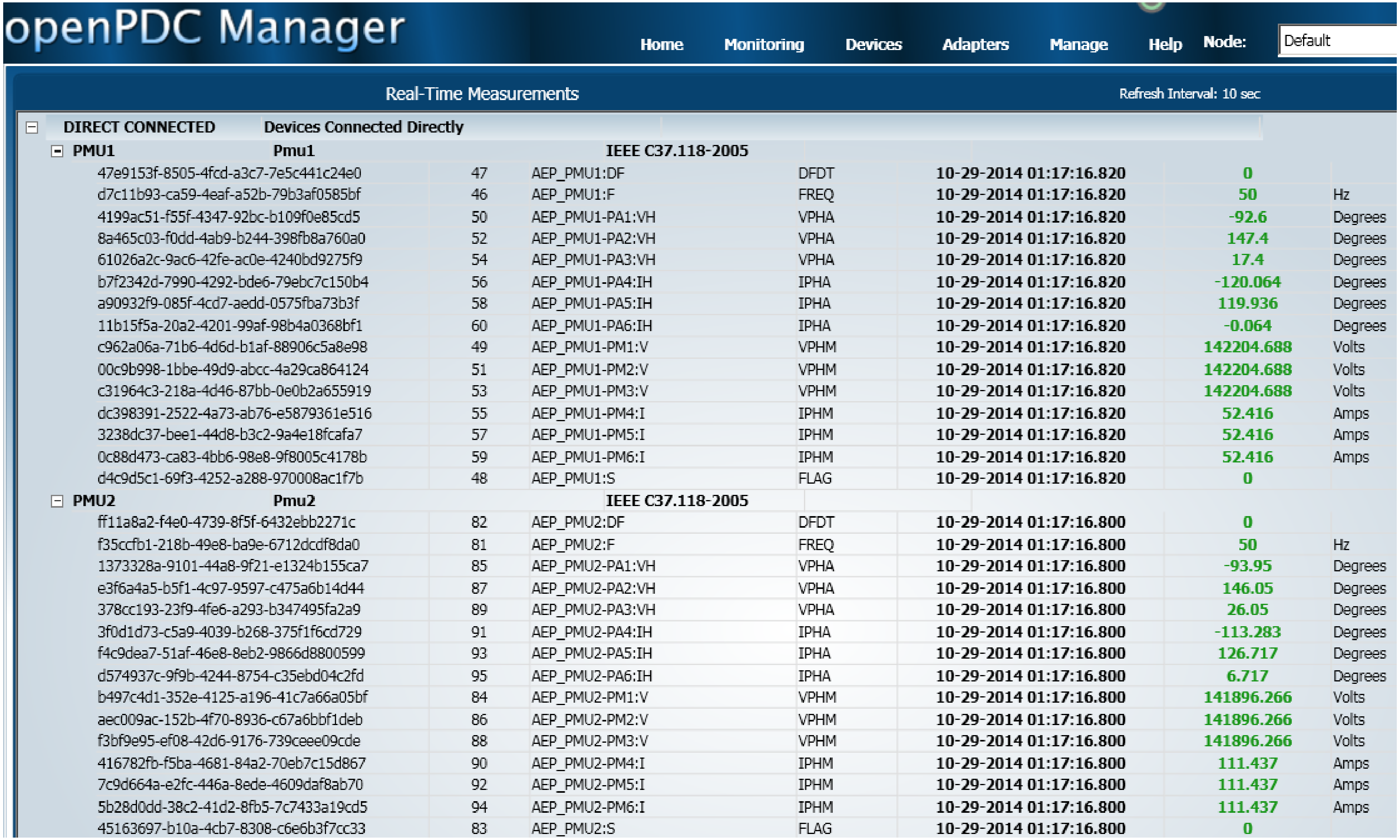
# Flow chart of Lagrange's algorithm for CEED problem



## 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



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




| | | | | | | |
|---|---|---|---|---|---|---|
| **DIRECT CONNECTED** | **Devices Connected Directly** | | | | | |
| **PMU1** | **Pmu1** | **IEEE C37.118-2005** | | | | |
| 47e9153f-8505-4fcd-a3c7-7e5c441c24e0 | 47 | AEP_PMU1:DF | DFDT | **10-29-2014 01:17:16.820** | **0** | |
| d7c11b93-ca59-4eaf-a52b-79b3af0585bf | 46 | AEP_PMU1:F | FREQ | **10-29-2014 01:17:16.820** | **50** | Hz |
| 4199ac51-f55f-4347-92bc-b109f0e85cd5 | 50 | AEP_PMU1-PA1:VH | VPHA | **10-29-2014 01:17:16.820** | **-92.6** | Degrees |
| 8a465c03-f0dd-4ab9-b244-398fb8a760a0 | 52 | AEP_PMU1-PA2:VH | VPHA | **10-29-2014 01:17:16.820** | **147.4** | Degrees |
| 61026a2c-9ac6-42fe-ac0e-4240bd9275f9 | 54 | AEP_PMU1-PA3:VH | VPHA | **10-29-2014 01:17:16.820** | **17.4** | Degrees |
| b7f2342d-7990-4292-bde6-79ebc7c150b4 | 56 | AEP_PMU1-PA4:IH | IPHA | **10-29-2014 01:17:16.820** | **-120.064** | Degrees |
| a90932f9-085f-4cd7-aedd-0575fba73b3f | 58 | AEP_PMU1-PA5:IH | IPHA | **10-29-2014 01:17:16.820** | **119.936** | Degrees |
| 11b15f5a-20a2-4201-99af-98b4a0368bf1 | 60 | AEP_PMU1-PA6:IH | IPHA | **10-29-2014 01:17:16.820** | **-0.064** | Degrees |
| c962a06a-71b6-4d6d-b1af-88906c5a8e98 | 49 | AEP_PMU1-PM1:V | VPHM | **10-29-2014 01:17:16.820** | **142204.688** | Volts |
| 00c9b998-1bbe-49d9-abcc-4a29ca864124 | 51 | AEP_PMU1-PM2:V | VPHM | **10-29-2014 01:17:16.820** | **142204.688** | Volts |
| c31964c3-218a-4d46-87bb-0e0b2a655919 | 53 | AEP_PMU1-PM3:V | VPHM | **10-29-2014 01:17:16.820** | **142204.688** | Volts |
| dc398391-2522-4a73-ab76-e5879361e516 | 55 | AEP_PMU1-PM4:I | IPHM | **10-29-2014 01:17:16.820** | **52.416** | Amps |
| 3238dc37-bee1-44d8-b3c2-9a4e18fcafa7 | 57 | AEP_PMU1-PM5:I | IPHM | **10-29-2014 01:17:16.820** | **52.416** | Amps |
| 0c88d473-ca83-4bb6-98e8-9f8005c4178b | 59 | AEP_PMU1-PM6:I | IPHM | **10-29-2014 01:17:16.820** | **52.416** | Amps |
| d4c9d5c1-69f3-4252-a288-970008ac1f7b | 48 | AEP_PMU1:S | FLAG | **10-29-2014 01:17:16.820** | **0** | |
| **PMU2** | **Pmu2** | **IEEE C37.118-2005** | | | | |
| ff11a8a2-f4e0-4739-8f5f-6432ebb2271c | 82 | AEP_PMU2:DF | DFDT | **10-29-2014 01:17:16.800** | **0** | |
| f35ccfb1-218b-49e8-ba9e-6712dcdf8da0 | 81 | AEP_PMU2:F | FREQ | **10-29-2014 01:17:16.800** | **50** | Hz |
| 1373328a-9101-44a8-9f21-e1324b155ca7 | 85 | AEP_PMU2-PA1:VH | VPHA | **10-29-2014 01:17:16.800** | **-93.95** | Degrees |
| e3f6a4a5-b5f1-4c97-9597-c475a6b14d44 | 87 | AEP_PMU2-PA2:VH | VPHA | **10-29-2014 01:17:16.800** | **146.05** | Degrees |
| 378cc193-23f9-4fe6-a293-b347495fa2a9 | 89 | AEP_PMU2-PA3:VH | VPHA | **10-29-2014 01:17:16.800** | **26.05** | Degrees |
| 3f0d1d73-c5a9-4039-b268-375f1f6cd729 | 91 | AEP_PMU2-PA4:IH | IPHA | **10-29-2014 01:17:16.800** | **-113.283** | Degrees |
| f4c9dea7-51af-46e8-8eb2-9866d8800599 | 93 | AEP_PMU2-PA5:IH | IPHA | **10-29-2014 01:17:16.800** | **126.717** | Degrees |
| d574937c-9f9b-4244-8754-c35ebd04c2fd | 95 | AEP_PMU2-PA6:IH | IPHA | **10-29-2014 01:17:16.800** | **6.717** | Degrees |
| b497c4d1-352e-4125-a196-41c7a66a05bf | 84 | AEP_PMU2-PM1:V | VPHM | **10-29-2014 01:17:16.800** | **141896.266** | Volts |
| aec009ac-152b-4f70-8936-c67a6bbf1deb | 86 | AEP_PMU2-PM2:V | VPHM | **10-29-2014 01:17:16.800** | **141896.266** | Volts |
| f3bf9e95-ef08-42d6-9176-739ceee09cde | 88 | AEP_PMU2-PM3:V | VPHM | **10-29-2014 01:17:16.800** | **141896.266** | Volts |
| 416782fb-f5ba-4681-84a2-70eb7c15d867 | 90 | AEP_PMU2-PM4:I | IPHM | **10-29-2014 01:17:16.800** | **111.437** | Amps |
| 7c9d664a-e2fc-446a-8ede-4609daf8ab70 | 92 | AEP_PMU2-PM5:I | IPHM | **10-29-2014 01:17:16.800** | **111.437** | Amps |
| 5b28d0dd-38c2-41d2-8fb5-7c7433a19cd5 | 94 | AEP_PMU2-PM6:I | IPHM | **10-29-2014 01:17:16.800** | **111.437** | Amps |
| 45163697-b10a-4cb7-8308-c6e6b3f7cc33 | 83 | AEP_PMU2:S | FLAG | **10-29-2014 01:17:16.800** | **0** | |

# PMU signal monitored in the RSCAD and MySQL environment for the initial loading condition

$$P_D = \sum_{i=1}^{m} V_{ia} I_{ia} \cos\left(\Phi_{ia1} - \Phi_{ia2}\right) + V_{ib} I_{ib} \cos\left(\Phi_{ib1} - \Phi_{ib2}\right) + V_{ic} I_{ic} \cos\left(\Phi_{ic1} - \Phi_{ic2}\right) \quad (12)$$

Where

$P_D$ - Total power demand in Watts

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

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

$\phi_{ia1}, \phi_{ia2}$ - Phase angle between the voltage and current in phase A for the $i^{th}$ load

$\phi_{ib1}, \phi_{ib2}$ - Phase angle between the voltage and current in phase B for the $i^{th}$ load

$\phi_{ic1}, \phi_{ic2}$ - Phase angle between the voltage and current in phase C for the $i^{th}$ load

| PMU voltage and current signals | | $V_a$ | $\delta_{va}$ | $V_b$ | $\delta_{vb}$ | $V_c$ | $\delta_{vc}$ | $I_a$ | $\delta_{Ia}$ | $I_b$ | $\delta_{Ib}$ | $I_c$ | $\delta_{Ic}$ | $P_D$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 |

## 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 |

## Economic dispatch problem solution using the GTNET card PMU signals

| $P_D$ in MW | 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 |

## 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

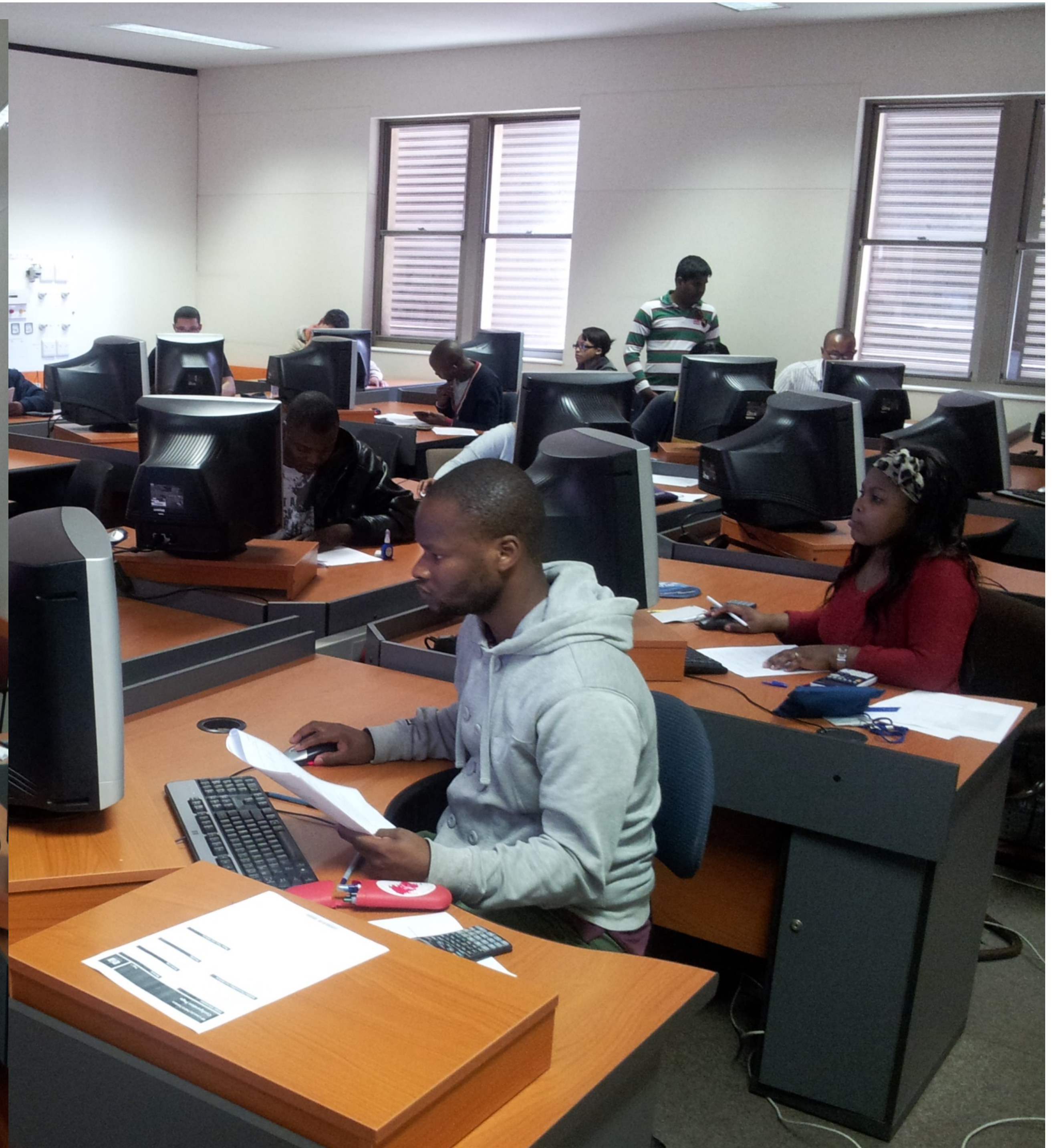
| $P_D$ in MW | Synchrophasor Technology using GTNET card PMU signals | | | | | RTDS PB5 card front panel analog output signals | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $P_L$ in MW | Lagrange's method | | Fuel cost in Rs/hr | | $P_D$ in MW | $P_L$ in MW | Number of iterations | 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 |

- 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)
- 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.

CSAEMS
Centre for Substation Automation and Energy Management Systems

# Teaching power system Protection course at University (CPUT) level using RTDS

1. Power system modeling and simulation using RTDS
2. To implement and analyse the fault analysis of the five bus power system network using RTDS
3. Implementation of the Distance Protection scheme using RTDS

# Conclusion

- The GTNET card PMU supports the IEEE C37.118-2005 standard which allows for the transfer of 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 transformation 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.
- 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.

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# Thank You


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