CHAPTER-5

IEC-61850 COMMUNICATION ASSISTED MONITORING, CONTROL AND PROTECTION OF DISTRIBUTION SYSTEMS USING PHASOR MEASUREMENT UNITS

5.1 INTRODUCTION

PMUs placed at the substation and DTs may be quite helpful in real time monitoring and control of distribution networks. In this chapter, two level control architecture of the distribution system proposed in Chapter 3 has been supplemented with PMUs. PMUs have been placed at the main substation as well as at DTs. Developed PMU model in MATLAB presented in Chapter 4 has been used to estimate phasors using Discrete Fourier Transform. Estimated voltage and current phasors together with frequency are transmitted from PMU at DTs to the local controllers and from PMU at the main substation to master controller through IEC-61850 communication protocol. Controllers perform different tasks based on the data received from PMUs. PMUs are also linked with the smart meters at consumer premises through Programmable Logic Controller (PLC) communication link. PLC communications were typically proprietary, with each supplier having their own closed connections and protocol (Ethernet TCP/IP).

5.2 PROPOSED ARCHITECTURE OF DISTRIBUTION NETWORK USING IEC-61850 COMMUNICATION PROTOCOL AND PMUs

The architecture of the proposed IEC-61850 communication assisted distribution system utilizing PMUs is shown in Fig. 5.1. In this architecture, Phasor Measurement Unit (PMU) has been placed at the main substation receiving supply from the grid through the incoming feeder, as well as at all distribution transformers (DTs). PMU installed at the main substation is linked to master controller (secondary controller) through IEC-61850 communication protocol. PMUs placed at DTs are connected to the corresponding local controller (primary controller) through the IEC-61850 communication protocol. Estimated voltage and current phasors together with frequency are transmitted from PMU at DTs to the local controller as well as from PMU at the main substation to master controller through an IEC-61850 communication protocol. Controllers perform different tasks based on the data received from PMUs. Each local controller is linked to master controller as well as to all smart meters placed at consumer premises. Bidirectional exchange of information takes place between master and local controllers as well as between local controller and smart meters.

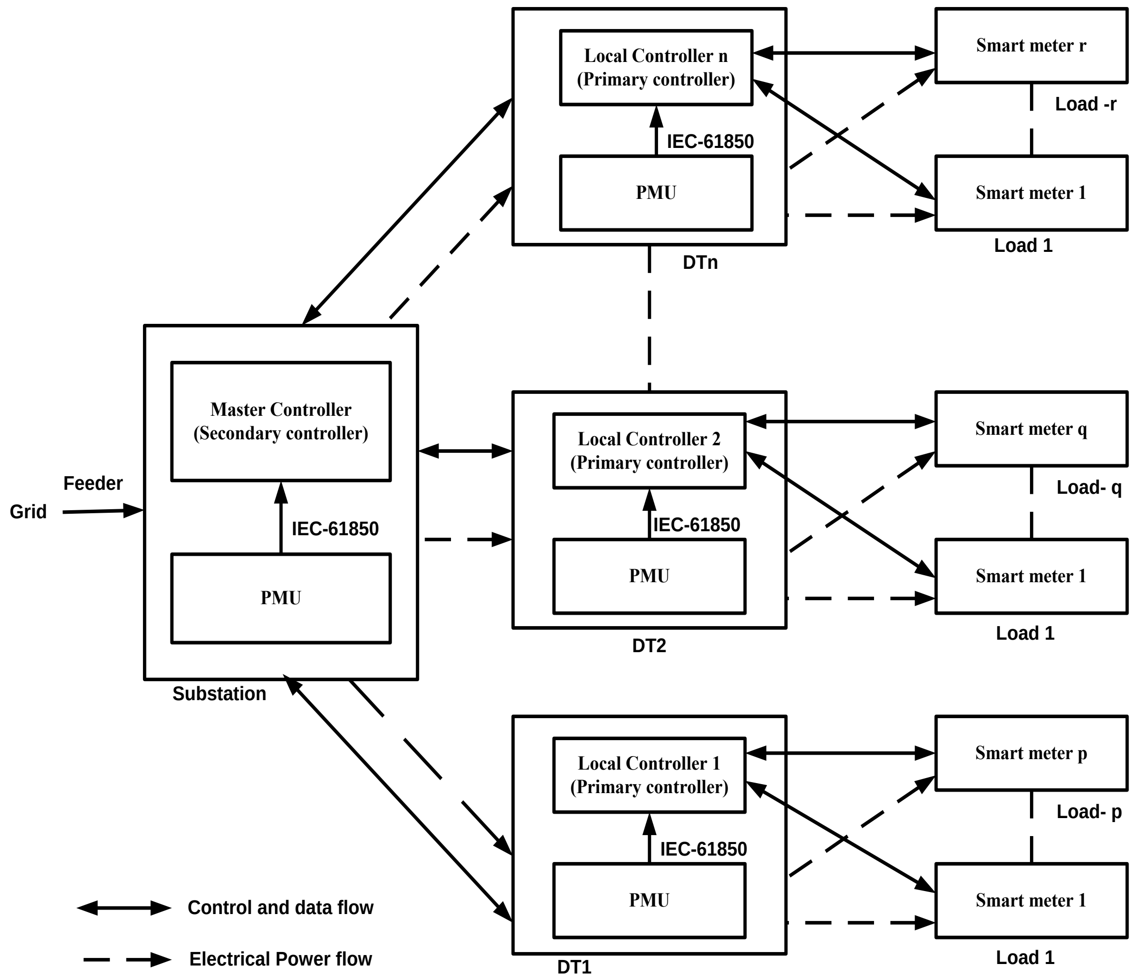

Fig. 5.1 The layout of the proposed distribution system

IEC-61850 is the normal communication protocol i.e. employed in substations for communications. It permits combination of control & protection beside its perceptive functions in substation, and conjointly delivers the resources for super-speed substation security uses, interlocking and inter-tripping. It conjointly permits the relays integration within the IEC-61850 based Substation Automation System (SAS) with numerous vendors Merging Unit (MU) above IEC-61850 Process Bus. It merges quality of Local Area Network (LAN) with its capability and protection that's crucial for substations these days. In this protocol, relays are inherent into the LAN/Ethernet card with the necessity of LAN equipments like grade switches. Generic Object Oriented Substation Event (GOOSE) messages is employed for inter-locking, disturbance recording cross-triggering, directional comparison bus protection, failure of breaker protection tripping beside numerous new progressive applications, this helps in removing widespread hardwiring in equipment inlets and helps in reducing the price of distributed protection and management schemes. The execution of IEC GOOSE electronic messaging provides high speed end-to-end transfer. The MUs set on substation yard interface with CTs/PTs sends the voltage/current sampled values over fiber, therefore, eliminating copper wires between primary substation equipments and management, protection, and measure devices. The devices of SAS are often organized in 3 levels, e.g., the station, bay and process level as shown in Fig. 5.2. Within the station level, a user-interface system with database/information, server, workstation, and engineering facilities is put in. The control & protection Intelligent Electronic Devices (IEDs), PMUs are put in at the bay level. Process level devices embrace the sensors, current/potential transformers, circuit breakers and MUs. IEC-61850 based protocols are mostly employed by substation automation facilities, e.g., GOOSE, Sampled Measured Values (SMV) and Manufacturing Message Specification (MMS). GOOSE is employed to send tripping signals from IEDs to circuit breakers. Sampled measured voltages and current values are sent from MU to an IED. Several devices are synchronic by GPS.

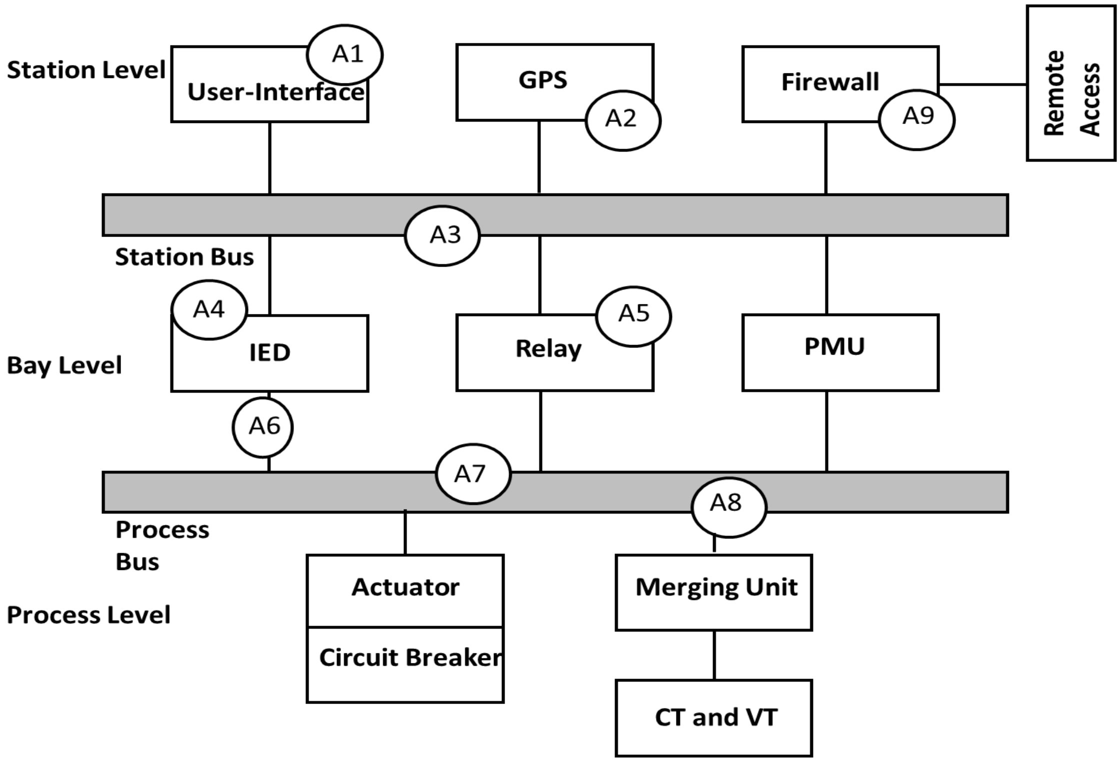

Fig. 5.2 Substation Automation System (SAS) through IEC-61850 Communication Protocol

The substation automation network as illustrated in Fig. 5.2 includes:

A1: Compromise user-interface

A2: Interrupt time synchronization

A3: Compromise station level communication bus

A4: Gain access to bay level devices

A5: change protective device settings

A6: Capture and modify GOOSE message

A7: Compromise process level communication bus

A8: Generate fabricated analog values (SV)

A9: Compromise firewall & gain access to substation

5.3 CASE STUDIES

Case studies were performed on a distribution test system shown in Fig. 3.3. Algorithm presented regarding load shedding/load reconnection based on available power were tested on a developed MATLAB/SIMULINK model of the test system as well as on an eMEGASim® OP5600 OPAL-RT real-time simulator. Simulation results are presented below.

IEC-61850 communication protocol is implemented using OPAL RT which is used as a communication interface to send data to a remote device and receive data from it. This communication protocol is used for communicating between a power system network (substation and distribution transformer) and control center (controller). The layout of the proposed distribution system with IEC-61850 communication protocol is shown in Fig. 5.3. In this work, IEC-61850 communication protocol has been used in Area 2 to send the data (voltage and current) at the substation and distribution transformer by using Op61850 Merging Unit Mask and SV Subscriber Mask blocks directly to the controller.

5.3.1 *Op61850 Merging Unit Mask*

The block ***"Op61850 Merging Unit Mask"*** is used to simulate an IEC-61850 Logical Device Merging Unit in a Substation Automation System. According to IEC-61850-9-2-LE document, a merging unit is an interface unit that accepts 4 CT/VT in input and produces time synchronized sampled values on the IEC-61850 network.

5.3.2 *Op61850 Sampled Values Subscriber Mask*

The block ***"Op61850 Sampled Values Subscriber Mask"*** is used to subscribe to IEC-61850 Sampled Value messages sent by Logical Device Merging Unit in a Substation

Automation System. Block's outputs provide 4 CT/VT time synchronized sampled values as well as the quality information.

The IEC-61850 communication networks and systems potency automation permits utilities to think about new styles for substations applicable for each new substation and refurbishments. IEC-61850 encompasses two buses supported by the LAN technology i.e. Station Bus and Process Bus shown in Fig. 5.3. Fig. 5.3 shows the abstract design of a whole IEC-61850 SAS. A high voltage substation supported IEC-61850 process bus shows particular network topology because it pretends to indicate the logical view of IEC-61850 specification. The figure illustrates physically separate networks for Station Bus and Process Bus IED's connected to each networks via freelance network interfaces. But it's potential is that Station Bus and Process Bus are within the same physical network sharing a typical set of LAN switches. The IEC-61850 Station Bus interconnects all bays with the station higher-up level and carries management in sequence like measurement, interlocking and operations. Station Bus introduces many advantages just like the use of GOOSE messages for quick transfer of essential protection information. GOOSE has been employed here for exchanging between IEDs interlocking and obstruction signals, as it permits reduction of copper wiring conventionally used for exchanging binary information among relays due to the use of Ethernet network. The IEC-61850 Process Bus interconnects the IEDs among a bay that carries real-time measurements for security known as Sampled Values (SV). Process Bus goes a step further than Station Bus because it provides the digital link to the apparatus like switchgear and instrument transformers. Relay panels have abundant less wiring that helps in regulate the sign of the interfaces between primary and secondary systems.

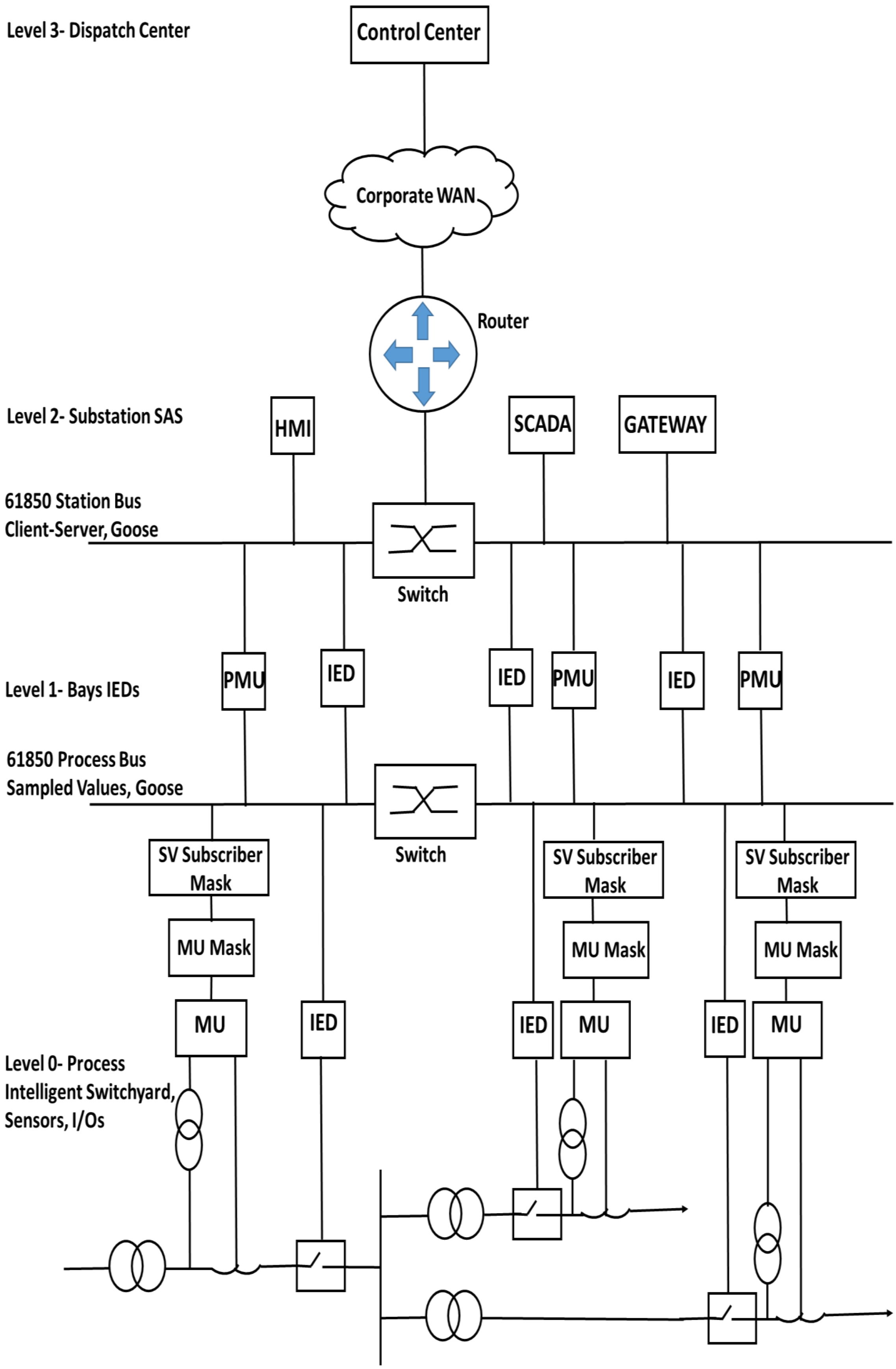

Fig. 5.3 Layout of the proposed distribution system with IEC-61850 Communication protocol

5.3.3 Phasor Measurement Unit (PMU)

The PMU calculates the phase, magnitude, frequency and Rate of Change of Frequency (ROCOF) of the positive sequence component of three-phase voltage/current signal. PMU block uses Phase Locked Loop (PLL) to determine the component of frequency and a positive-sequence measurement over a running window of one cycle of the fundamental frequency. Input to the PMU is the three-phase signal (p.u.) with 50Hz nominal frequency. The three outputs of the PMU block is the magnitude of the positive-sequence signal (p.u.), phase (degrees relative to the PLL phase) and frequency (Hz). The PMU block is inspired by C37.118.1-2011 Std. of IEEE. Here, the PMU is placed at the substation and distribution transformer to determine the available power at the substation and at distribution transformer.

5.3.3.1 Available power at the substation with the help of PMU

Simulation results for calculation of available power through PMU in real-time at the substation by considering the load disconnection/connection based on available power (from time t = 0.56sec to time t = 0.75sec), protection of feeder against overcurrent (from time t = 0.15sec to time t = 0.20sec), and Power theft detection and elimination (from time t = 0.21sec to time t = 0.23sec) have been shown below. Overcurrent in phase A was produced by connecting an extra load of 150 kW and 150 kVAr to load number 1 of area 1. Power theft in phase C was created by connecting an illegal load of 150 kW and 80 kVAr.

5.3.3.1.1 Input voltage and current to PMU at substation

The input three-phase voltage signal V_{rms} = 2688V with 50Hz nominal frequency at the substation is shown in Fig. 5.4.

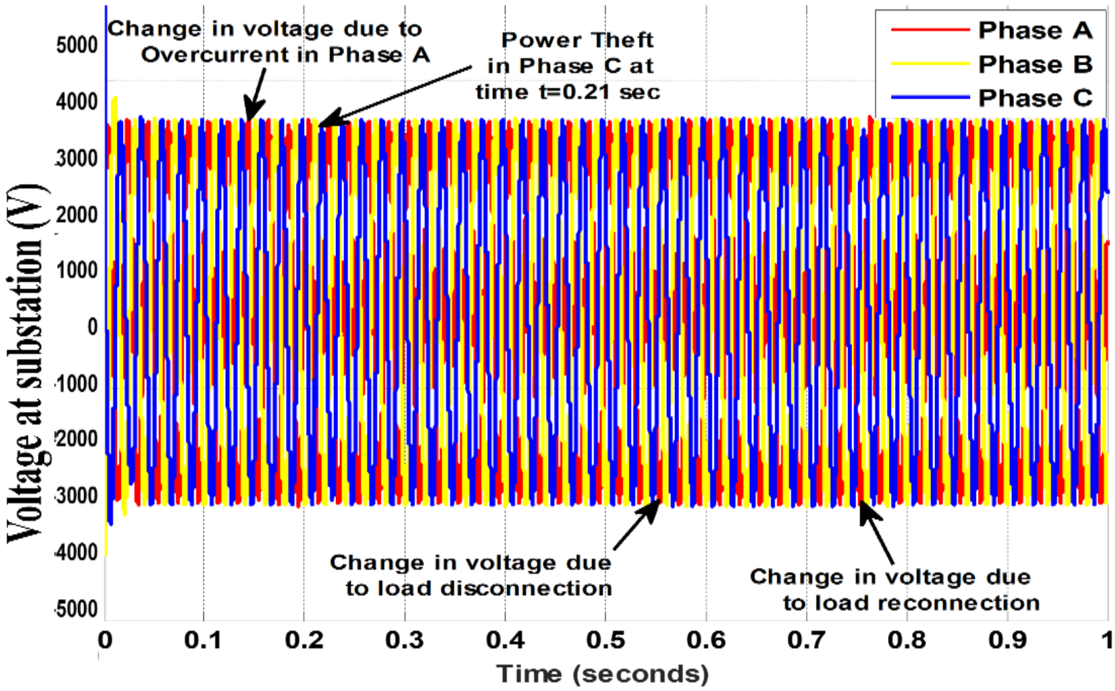

Fig. 5.4 Input voltage to PMU at the substation

The input three-phase current signal I_{rms} = 240.45A with 50Hz nominal frequency at the substation is shown in Fig. 5.5. It is observed from Fig. 5.5, that there is an overcurrent from time t = 0.15sec to time t = 0.20sec due to the connection of an extra load consisting of real power demand and reactive power demand of 150kW and 150kVAr, respectively, to load number 1 of phase A in area 1. Also, there is power theft in Phase C, due to the connection of illegal load of real and reactive power load of 150kW and 80kVAr respectively at time t = 0.21sec which was removed at time t = 0.23sec. It is also observed from Fig. 5.5 that the load is disconnected based on available power from time t = 0.56sec and is reconnected at time t = 0.75sec.

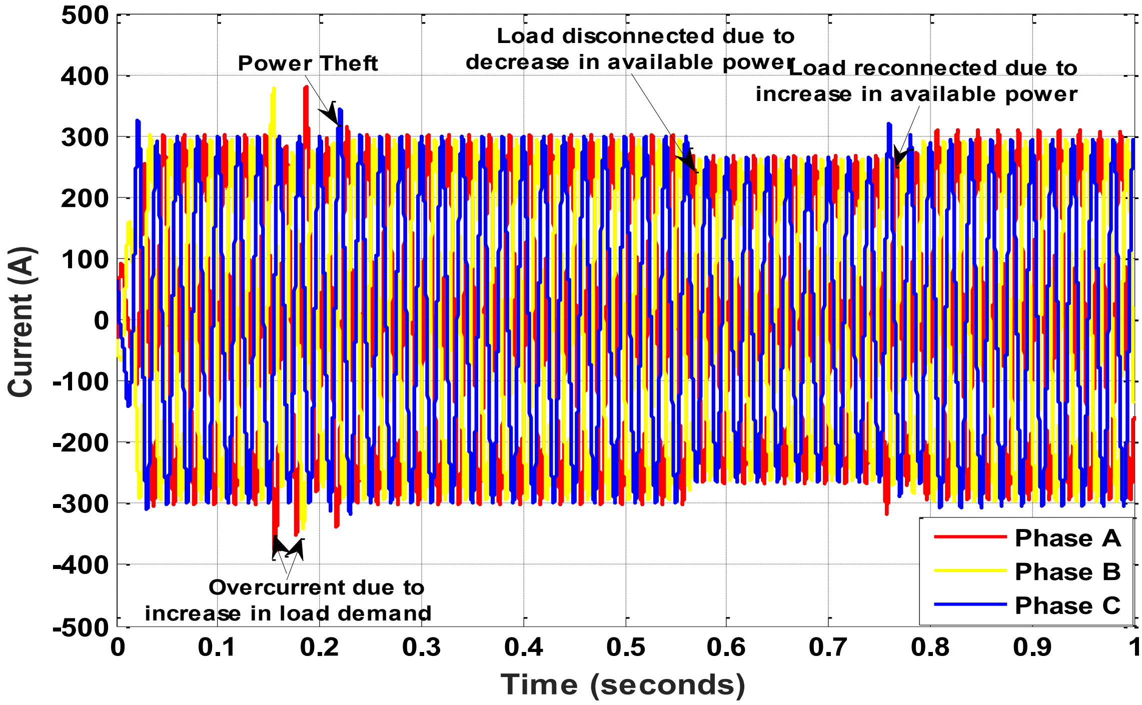

Fig. 5.5 Input current to PMU at the substation

5.3.3.1.2 PMU output- Magnitude of the voltage and current at substation:

The magnitude of the positive-sequence voltage signal at the substation is shown in Fig. 5.6. It is observed from Fig. 5.6 that the voltage magnitude changes quite rapidly at the starting. This is due to the switching of induction motor loads.

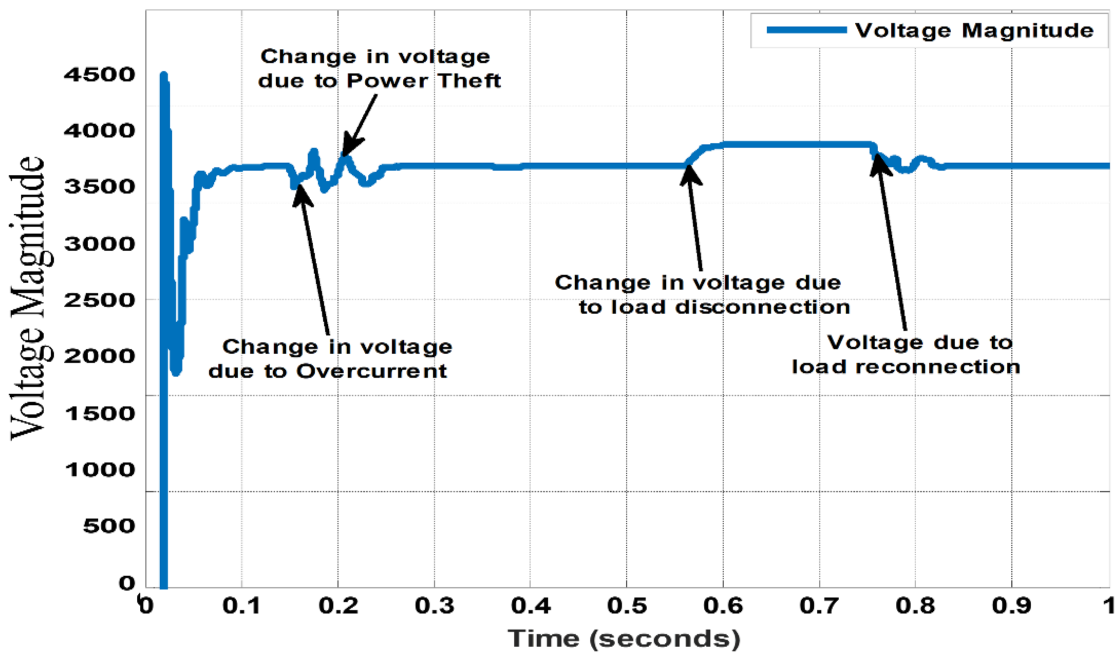

Fig. 5.6 Magnitude of the voltage at substation

The magnitude of the positive-sequence current signal at the substation is shown in Fig. 5.7. And, it is observed from the magnitude of current in Fig. 5.7, that there is an overcurrent from time t = 0.15sec to time t = 0.20sec due to the connection of an extra load consisting of real power demand and reactive power demand of 150kW and 150kVAr, respectively, to load number 1 of phase A in area 1. Also, there is power theft in Phase C, due to the connection of illegal load of real and reactive power load of 150kW and 80kVAr respectively at time t = 0.21sec which was removed at time t = 0.23sec. It is also observed from Fig. 5.7 that the load is disconnected based on available power from time t = 0.56sec and is reconnected at time t = 0.75sec.

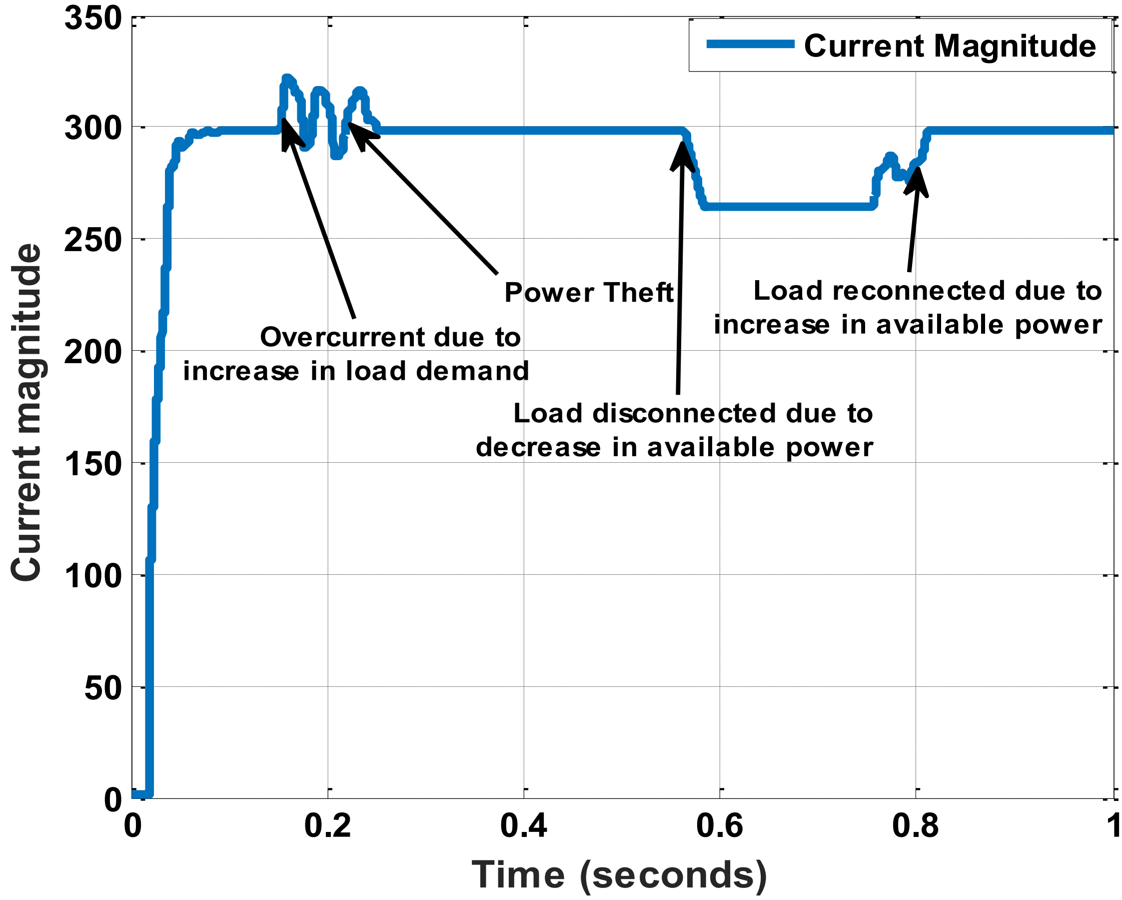

Fig. 5.7 Magnitude of current at the substation

5.3.3.1.3 PMU output- Phase angle of voltage and current at substation

The phase angle (degrees relative to the PLL phase) of the three-phase voltage signal at the substation is shown in Fig. 5.8. And, it is observed from Fig. 5.8 that the phase angle w.r.t. time reaches to -0.78 degree due to transients at the instant of starting and then it becomes normal with some variations due to variations in load.

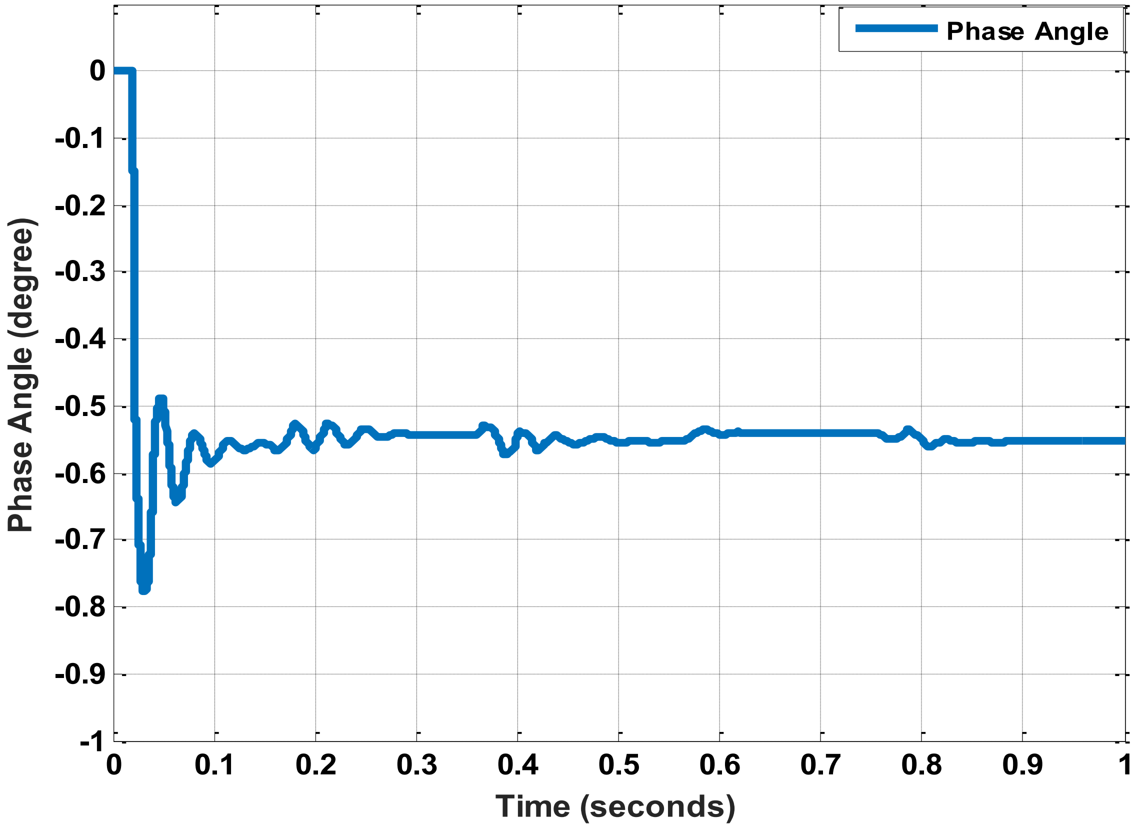

Fig. 5.8 The phase angle of the voltage at substation

The phase angle (degrees relative to the PLL phase) of the three-phase current signal at the substation is shown in Fig. 5.9. And, it is observed from Fig. 5.9 that the phase angle w.r.t. time reaches to -59.89 degree due to transients at the instant of starting and then it becomes normal with some variations due to variations in load.

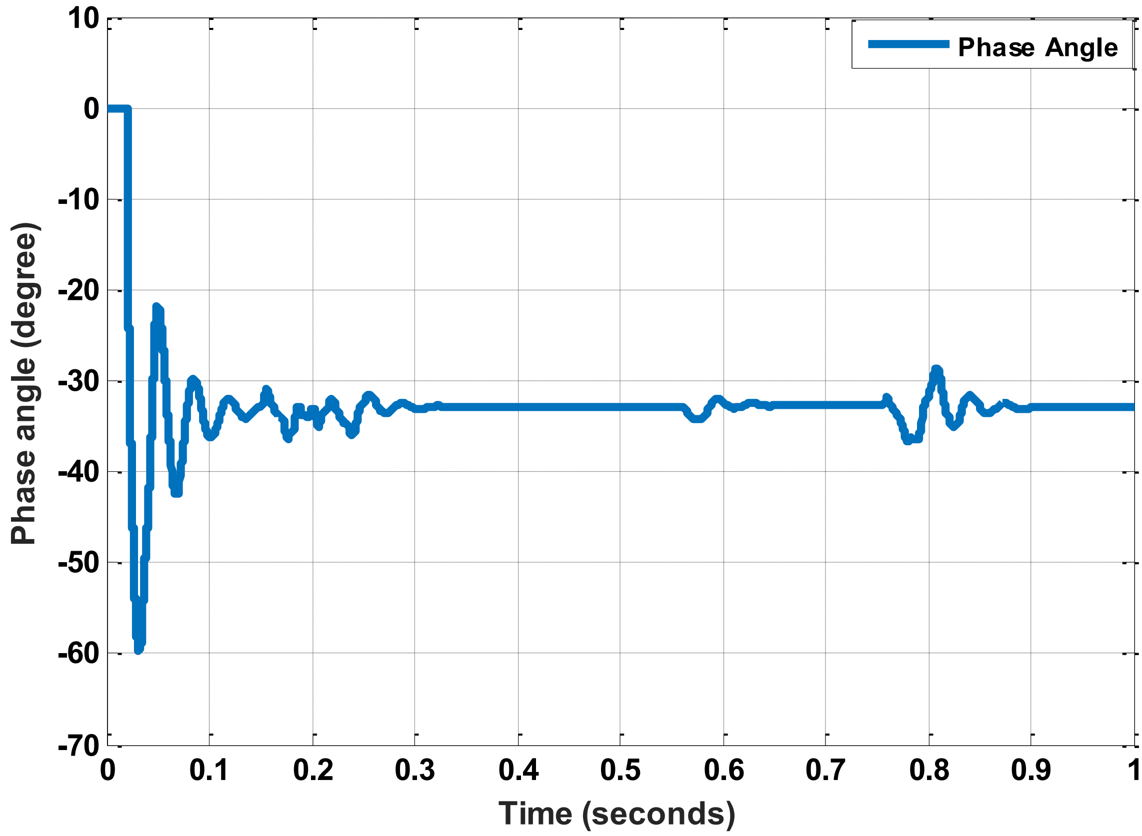

Fig. 5.9 The phase angle of current at the substation

5.3.3.1.4 PMU output- Frequency (Hz) of voltage and current at substation

According to the Standards for Power Frequency in India, the nominal frequency of operation in Indian grid is 50.0 Hz and the permissible frequency band specified by Indian Electricity Grid Code (IEGC) is 49.5Hz to 50.2Hz. The frequency (Hz) of the three-phase voltage signal at the substation is shown in Fig. 5.10. And, it is observed from Fig. 5.10, that frequency of voltage signal at substation varies from 49.9Hz to 50.03Hz i.e. within the permissible frequency band specified by IEGC.

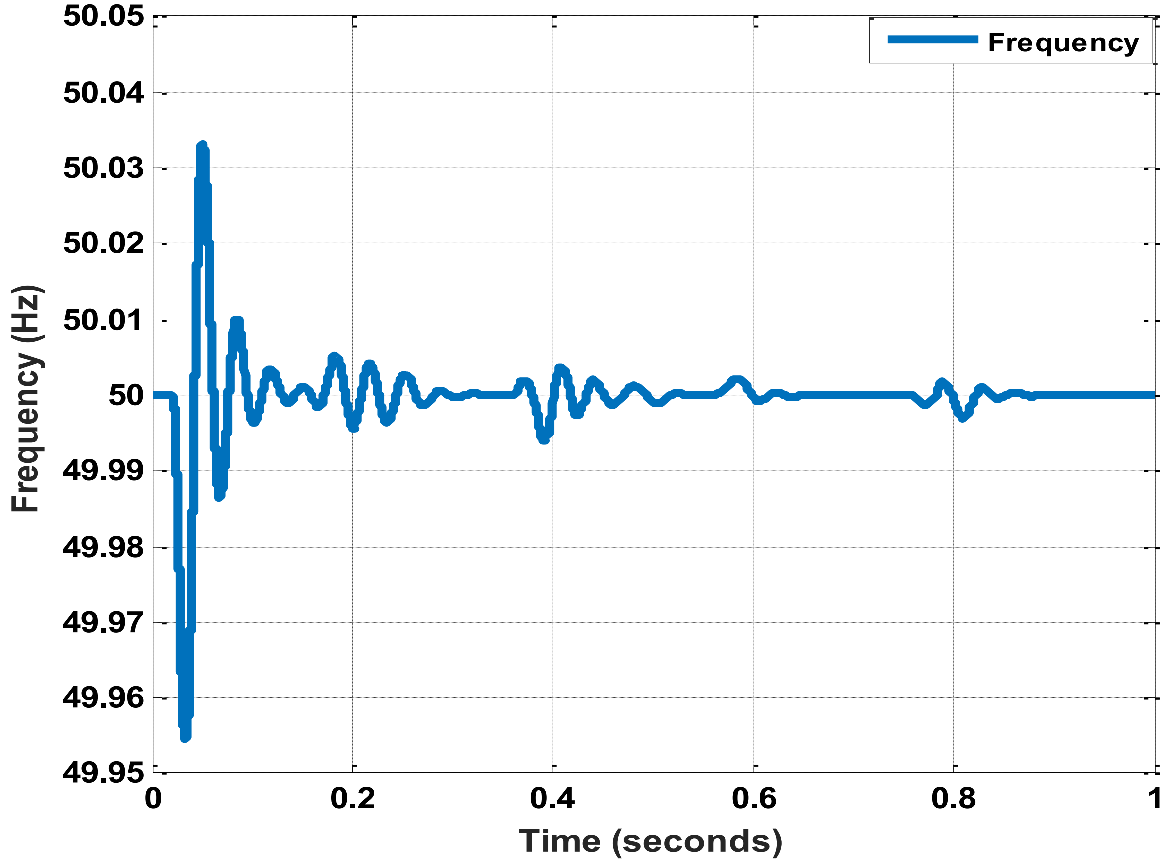

Fig. 5.10 The rate of change of frequency of the voltage at the substation

The frequency (Hz) of the three-phase current signal at the substation is shown in Fig. 5.11. And, it is observed from Fig. 5.11, that the frequency of current signal is within the permissible frequency band specified by Indian Electricity Grid Code (IEGC) but there is a slight variation in frequency due to overcurrent from time t = 0.15sec to time t = 0.20sec. It is seen from the fig. 5.11, that load is disconnected from time t = 0.56sec and is reconnected from time t = 0.75sec.

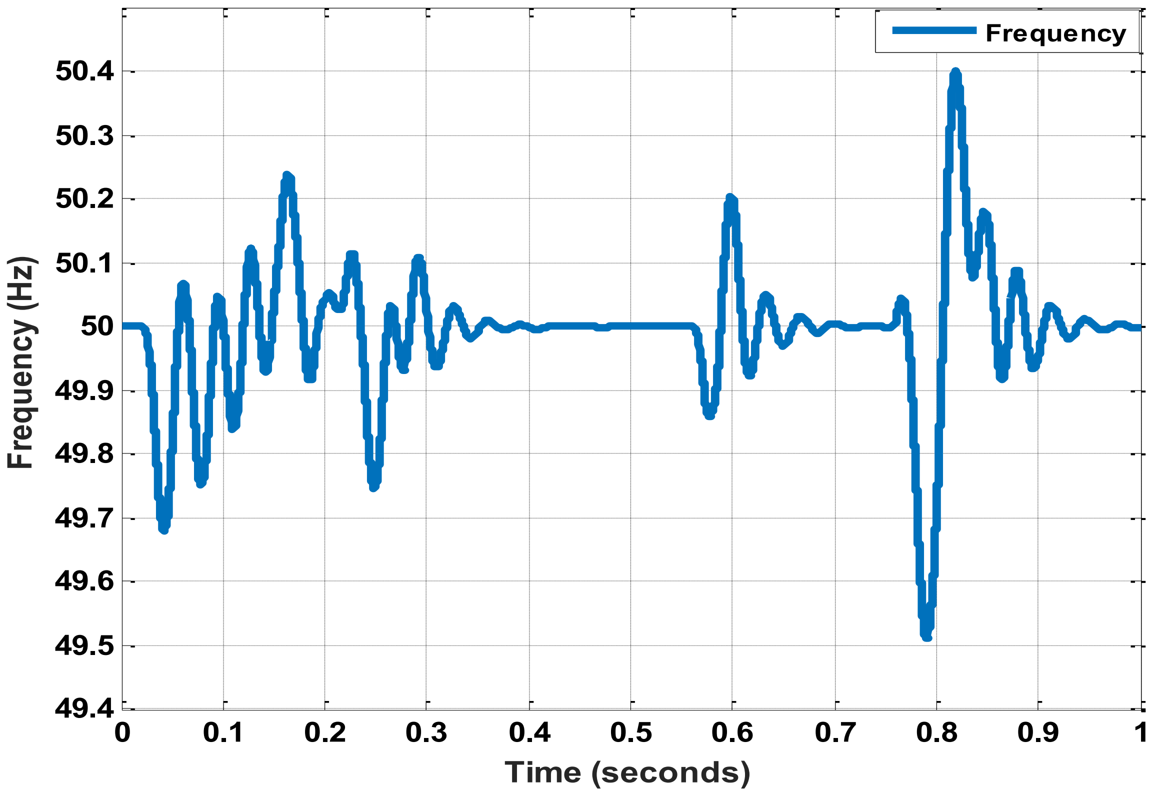

Fig. 5.11 The rate of change of frequency of the current at the substation

5.3.3.1.5 Power factor and available power at the substation

The power factor at the substation is shown in Fig. 5.12. It is observed from Fig. 5.12, that power factor reaches to 0.51 due to transients at the instant of starting and after that power factor at the substation maintains between ranges 0.8 to 0.9.

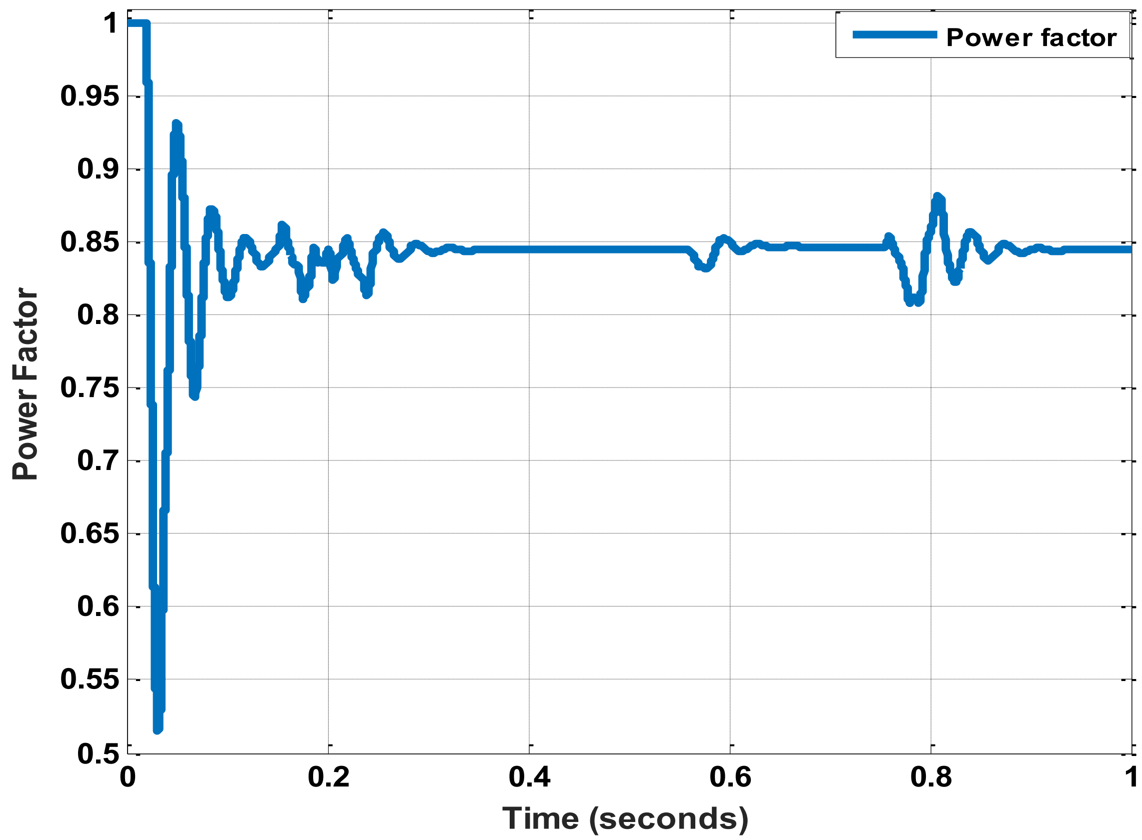

Fig. 5.12 Power factor at the substation

The available power at the substation is shown in Fig. 5.13. Available power in a phase ($P_{available}$) at the substation is given by equation (3.2) i.e. $P_{available} = V_{ph}\ I_{ph}\ \cos Ø$. It is observed from Fig. 5.13, that the reduction of supply voltage/power factor at the substation causes loss of available power, thus requiring load shedding to be performed.

The master controller continuously checked total available power at the substation and decided the distribution of available power to distribution transformers DT_1 and DT_2 connected to two areas based on the total connected load in each area. It is observed from Fig. 5.13 that available power drops from 3.2MW to 2.8MW at time t = 0.56sec. Since available power is less than total connected load by 11.3%, master controller present at substation instructs local controller at DT_1 to perform load shedding as per algorithm. It is observed from Fig. 5.13 that available power is recovered to 3.2MW at time t = 0.75sec.

So, load is disconnected based on available power from time t = 0.56sec and is reconnected at time t = 0.75sec.

It is observed from Fig. 5.13, that there is an overcurrent from time t = 0.15sec to time t = 0.20sec due to the connection of an extra load consisting of real power demand and reactive power demand of 150kW and 150kVAr, respectively, to load number 1 of phase A in area 1. Also, there is power theft in Phase C, due to the connection of illegal load of real and reactive power load of 150kW and 80kVAr respectively at time t = 0.21sec and was removed at time t = 0.23sec.

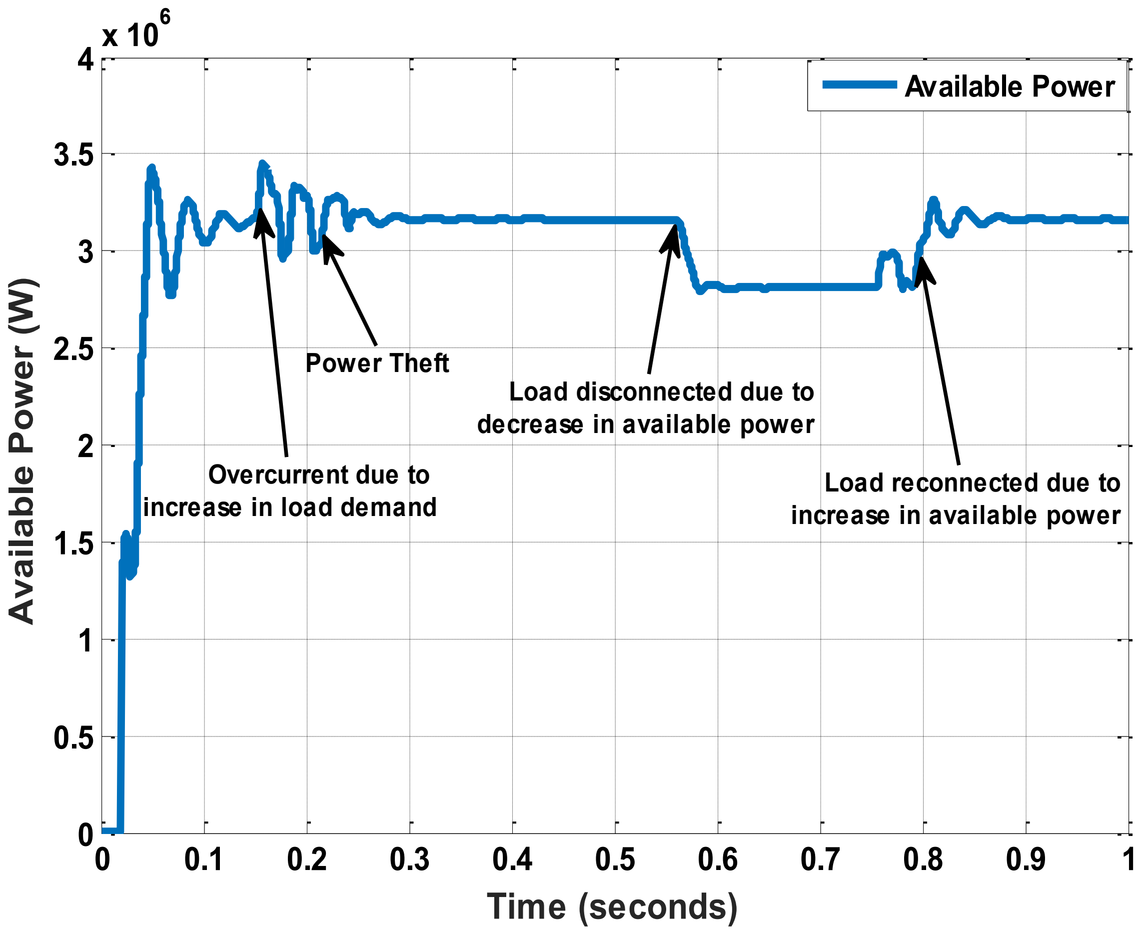

Fig. 5.13 Available power at the substation

5.3.3.2 *Available power at the distribution transformer with the help of PMU*

Simulation results for calculation of available power through PMU in real-time at the distribution transformer by considering the load disconnection/connection based on available power (from time t = 0.56sec to time t = 0.75sec), protection of feeder against overcurrent (from time t = 0.15sec to time t = 0.20sec), and Power theft detection and elimination (from time t = 0.21sec to time t = 0.23sec) have been shown below.

5.3.3.2.1 *Input voltage and current to PMU at DT_1*

The input three-phase voltage signal V_{rms} = 170V with 50Hz nominal frequency at DT_1 is shown in Fig. 5.14.

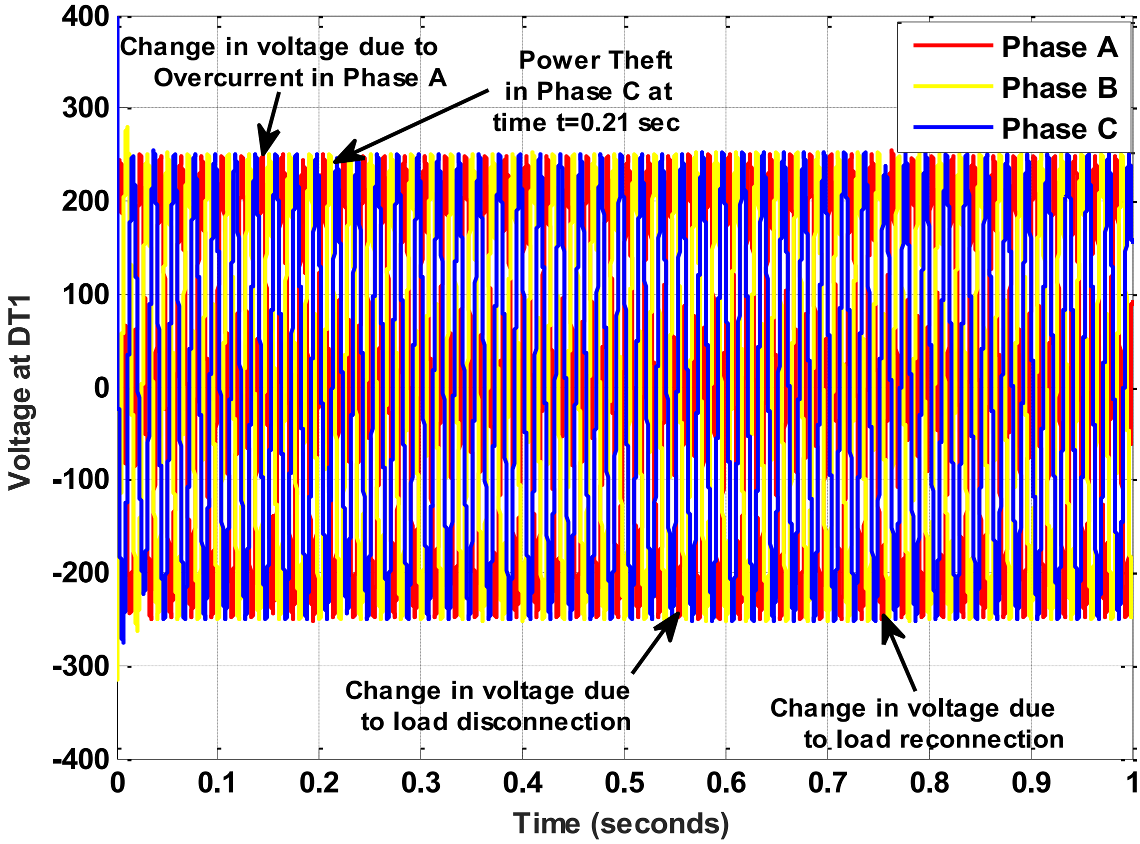

Fig. 5.14 Input voltage to PMU at DT_1

The input three-phase current signal I_{rms} = 2475.24A with 50Hz nominal frequency at the DT_1 is shown in Fig. 5.15. It is observed from Fig. 5.15, that there is an overcurrent from time t = 0.15sec to time t = 0.20sec due to the connection of an extra load consisting of real power demand and reactive power demand of 150kW and 150kVAr, respectively, to load number 1 of phase A in area 1. Also, there is power theft in Phase C, due to the connection of illegal load of real and reactive power load of 150kW and 80kVAr respectively at time t = 0.21sec and was removed at time t = 0.23sec. It is also observed from Fig. 5.15 that the load is disconnected based on available power from time t = 0.56sec and is reconnected at time t = 0.75sec.

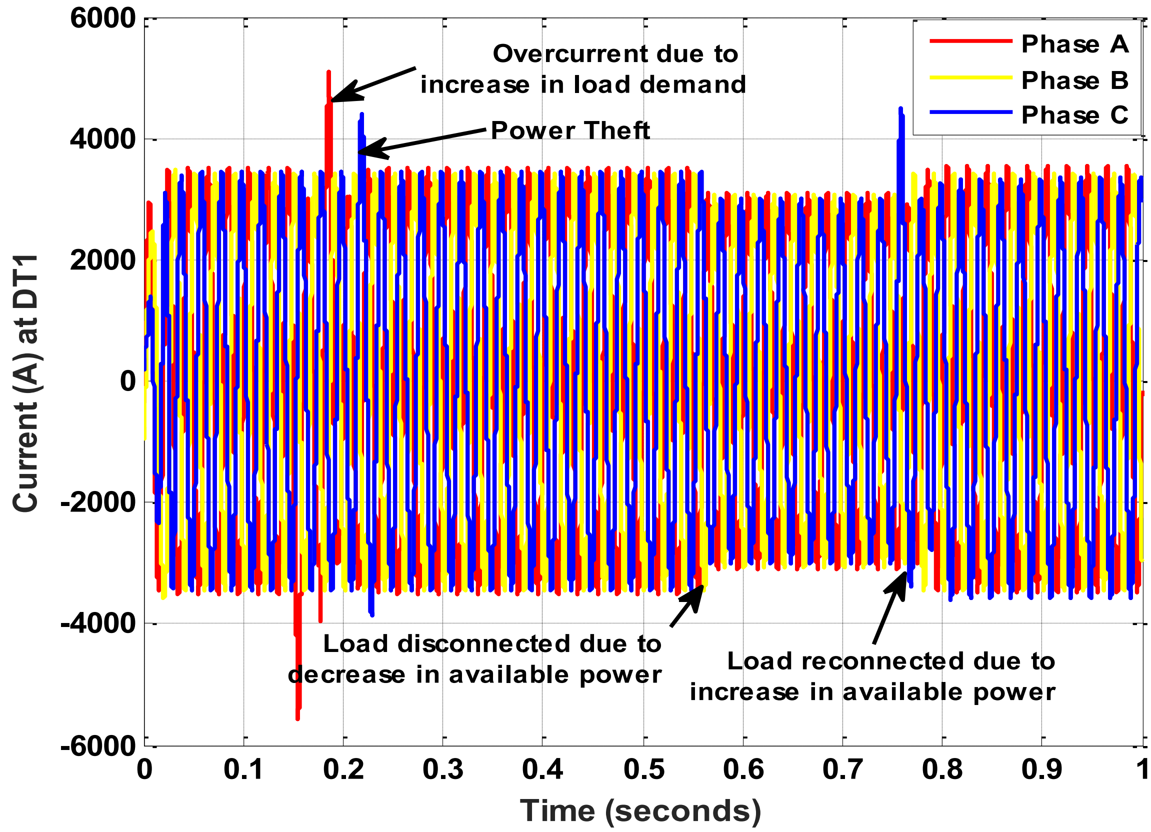

Fig. 5.15 Input current to PMU at DT_1

5.3.3.2.2 PMU output- Magnitude of voltage and current at DT_1

The magnitude of the positive-sequence voltage signal at DT_1 is shown in Fig. 5.16.

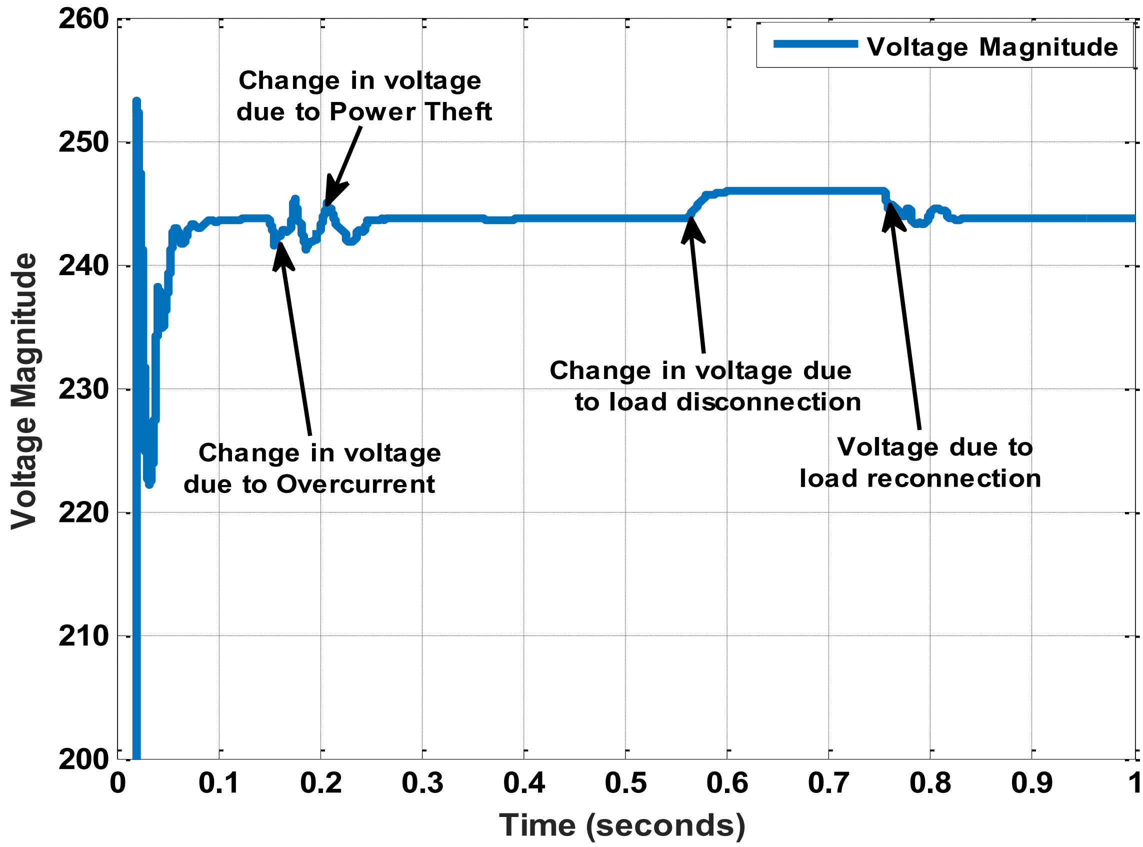

Fig. 5.16 Magnitude of the voltage at DT_1

The magnitude of the positive-sequence current signal at the DT_1 is shown in Fig. 5.17. And, it is observed from the magnitude of current in Fig. 5.17, that there is an overcurrent from time t = 0.15sec to time t = 0.20sec due to the connection of an extra load consisting of real power demand and reactive power demand of 150kW and 150kVAr, respectively, to load number 1 of phase A in area 1. Also, there is power theft in Phase C, due to the connection of illegal load of real and reactive power load of 150kW and 80kVAr respectively at time t = 0.21sec and was removed at time t = 0.23sec. It is also observed from Fig. 5.17 that the load is disconnected based on available power from time t = 0.56sec and is reconnected at time t = 0.75sec.

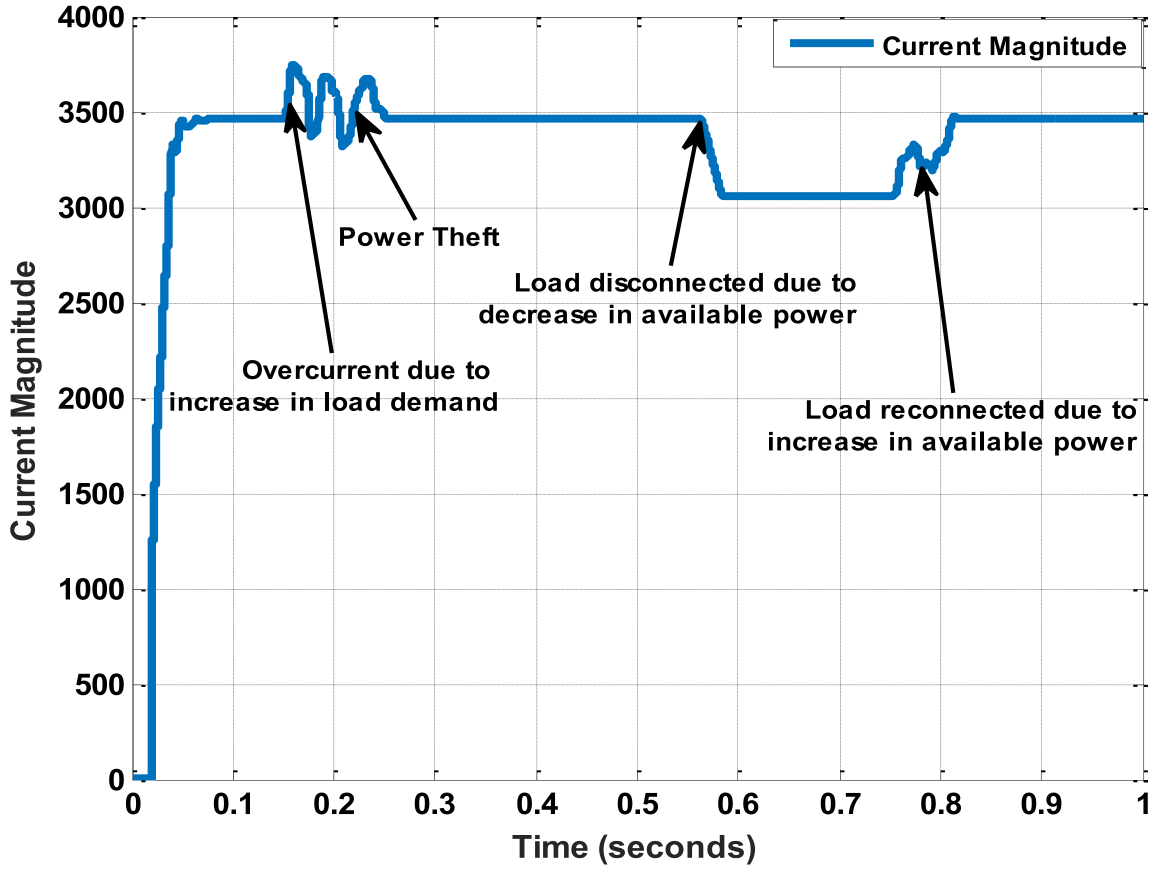

Fig. 5.17 The magnitude of the current at DT_1

5.3.3.2.3 PMU output- Phase angle of voltage and current at DT_1

The phase (degrees relative to the PLL phase) of the three-phase voltage signal at the DT_1 is shown in Fig. 5.18. And, it is observed from Fig. 5.18 that the phase angle w.r.t. time reaches to 46 degree due to transients at the instant of starting and then it becomes normal with some variations due to variations in load.

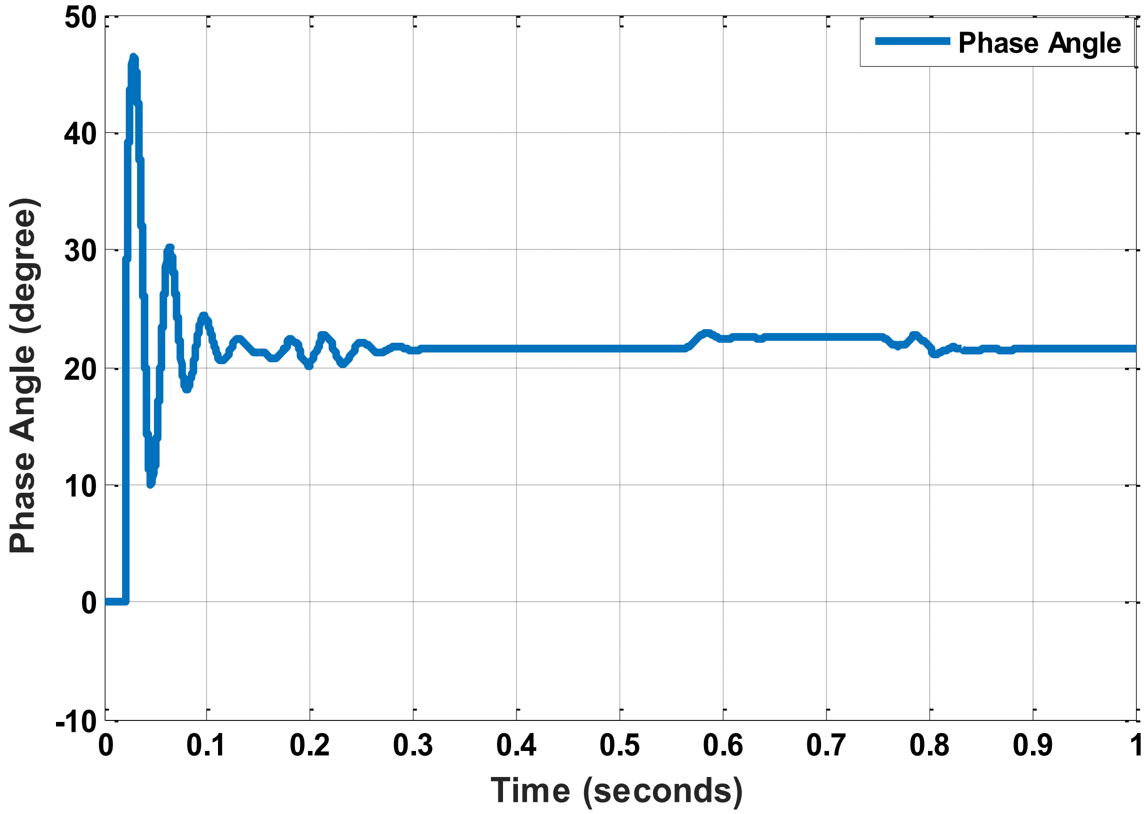

Fig. 5.18 The phase angle of the voltage at DT_1

The phase (degrees relative to the PLL phase) of the three phase current signal at the DT_1 is shown in Fig. 5.19. And, it is observed from Fig. 5.19 that the phase angle w.r.t. time varies from -15 to 7 degree due to transients at the instant of starting and then it becomes normal with some variations due to variations in load.

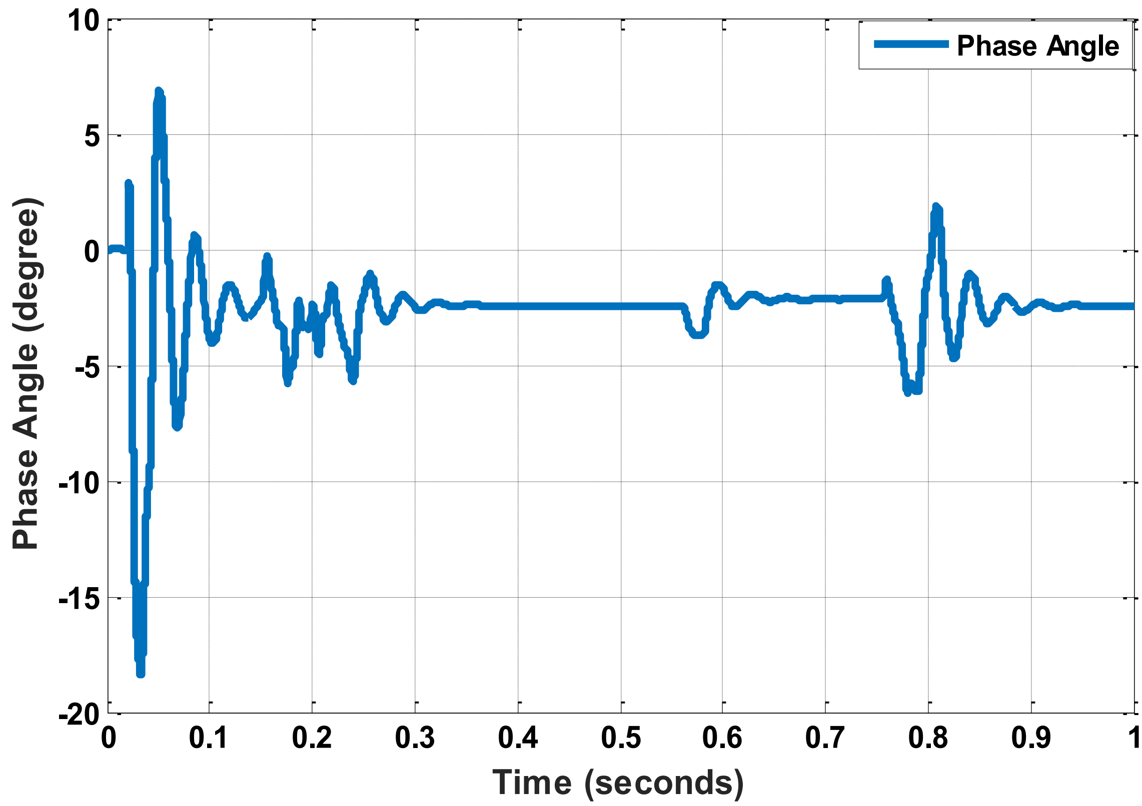

Fig. 5.19 The phase angle of current at DT_1

5.3.3.2.4 PMU output- Frequency of voltage and current at DT_1

The frequency (Hz) of the three-phase voltage signal at the DT_1 is shown in Fig. 5.20. According to the Standards for Power Frequency in India, the nominal frequency of operation in Indian grid is 50.0 Hz and the permissible frequency band specified by Indian Electricity Grid Code (IEGC) is 49.5Hz to 50.2Hz. The frequency (Hz) of the three-phase voltage signal at the DT_1 is shown in Fig. 5.20. And, it is observed from Fig. 5.20, that frequency of voltage signal at DT_1 varies from 49.8Hz to 50.2Hz i.e. within the permissible frequency band specified by IEGC.

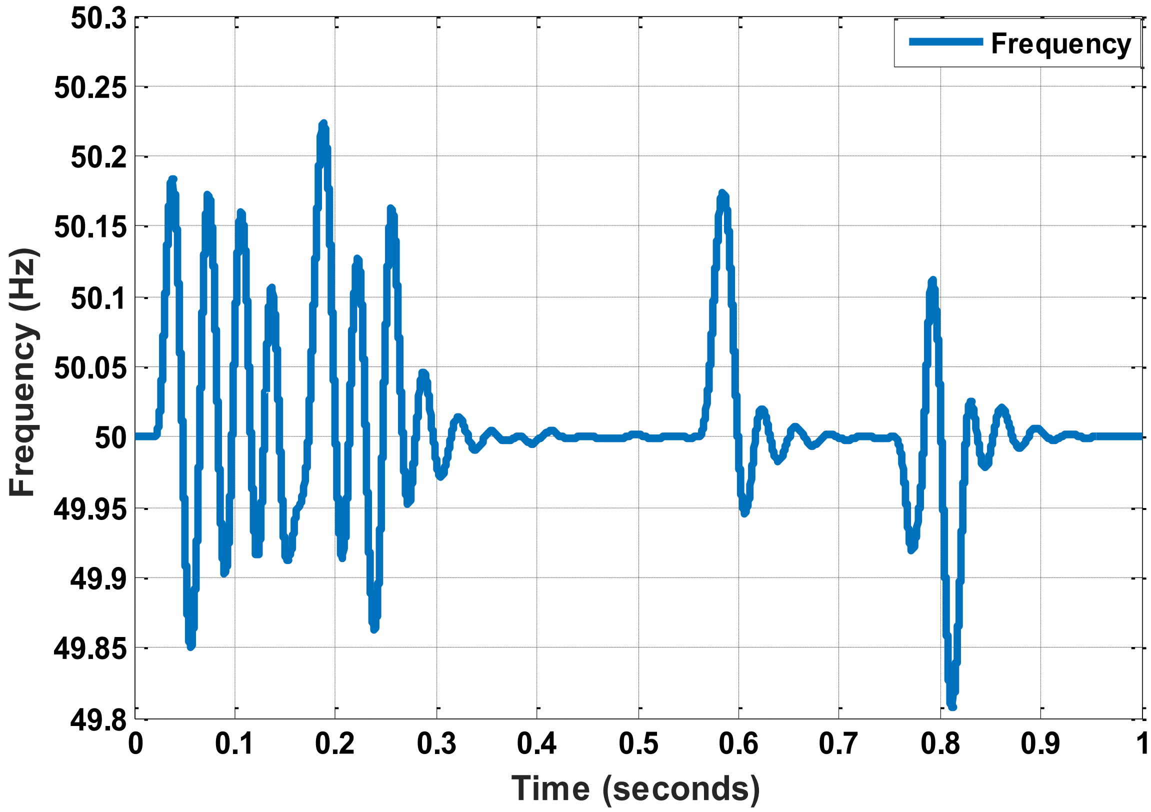

Fig. 5.20 The rate of change of frequency of the voltage at DT_1

The frequency (Hz) of the three-phase current signal at the DT_1 is shown in Fig. 5.21. And, it is observed from Fig. 5.21, that the frequency of current signal is within the permissible frequency band specified by IEGC but there is a slight variation in frequency due to the disconnection of load from time t = 0.56sec and its reconnection from time t = 0.75sec. After reconnection of load there is slight increase in the frequency which crosses the permissible frequency band specified by IEGC, so there is need of frequency control. So, at time t = 0.82sec by using load frequency control method, the frequency comes within the permissible frequency band specified by IEGC.

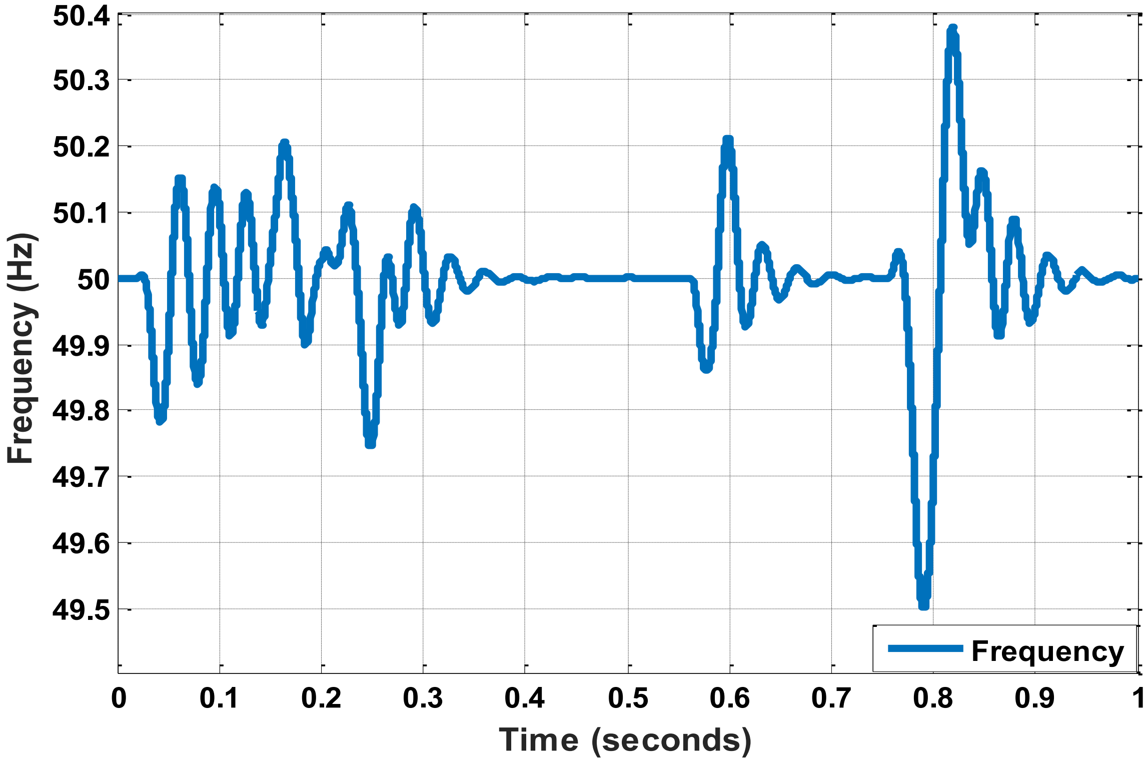

Fig. 5.21 The rate of change of frequency of the current at DT_1

5.3.3.2.5 Power factor and available power at DT_1

The power factor at DT_1 is shown in Fig. 5.22. It is observed from Fig. 5.22, that power factor reaches to 0.46 due to transients at the instant of starting and after that power factor at the DT_1 maintains between ranges 0.89 to 0.95.

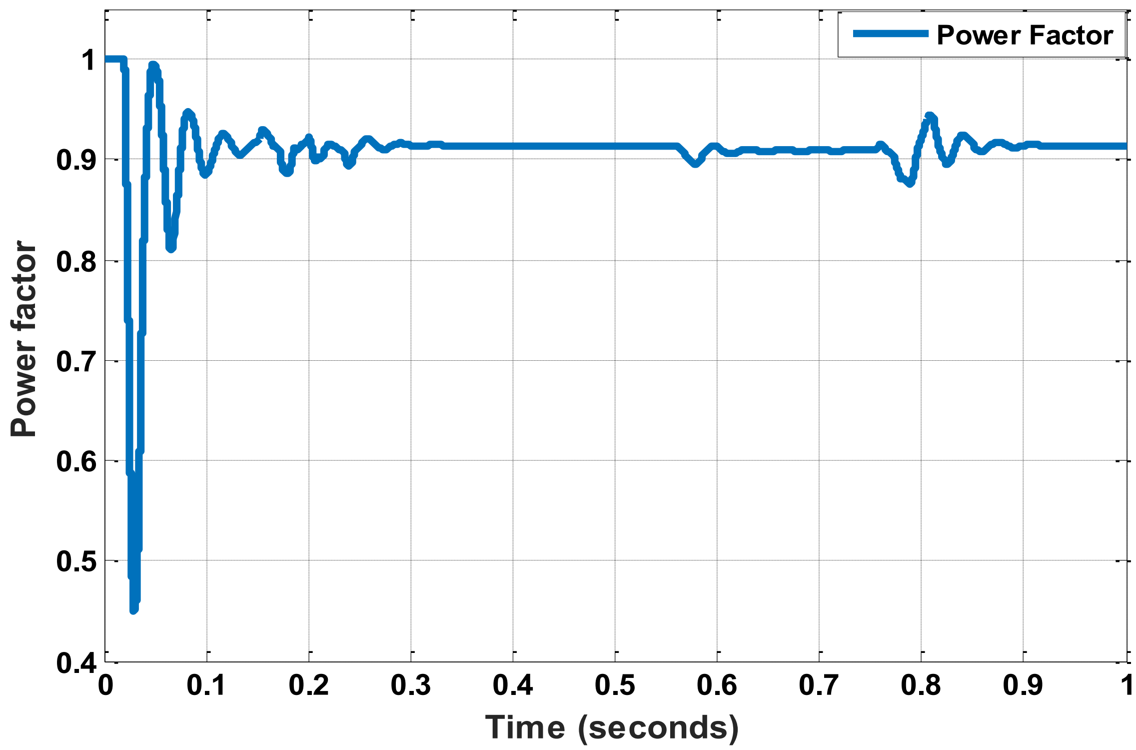

Fig. 5.22 Power factor at DT_1

The available power at the substation is shown in Fig. 5.23. Available power in a phase ($P_{available}$) at the DT_1 is given by equation (3.2) i.e. $P_{available} = V_{ph}\, I_{ph} \cos\emptyset$. It is observed from Fig. 5.23, that the reduction of supply voltage/power factor at the substation causes loss of available power, thus requiring load shedding to be performed.

The master controller continuously checked total available power at the substation and decided the distribution of available power to distribution transformers DT_1 and DT_2 connected to two areas based on the total connected load in each area. It is observed from Fig. 5.23 that available power drops from 2.4MW to 2.09MW at time t = 0.56sec. Since available power is less than total connected load by 11.3%, master controller present at substation instructs local controller at DT_1 to perform load shedding as per algorithm. It is observed from Fig. 5.23 that available power is recovered to 2.4MW at time t=0.75sec. So, load is disconnected based on available power from time t = 0.56sec and is reconnected at time t = 0.75sec.

It is observed from Fig. 5.23, that there is an overcurrent from time t = 0.15sec to time t = 0.20sec due to the connection of an extra load consisting of real power demand and reactive power demand of 150kW and 150kVAr, respectively, to load number 1 of phase A in area 1. Also, there is power theft in Phase C, due to the connection of illegal load of real and reactive power load of 150kW and 80kVAr respectively at time t = 0.21sec that was removed at time t = 0.23sec.

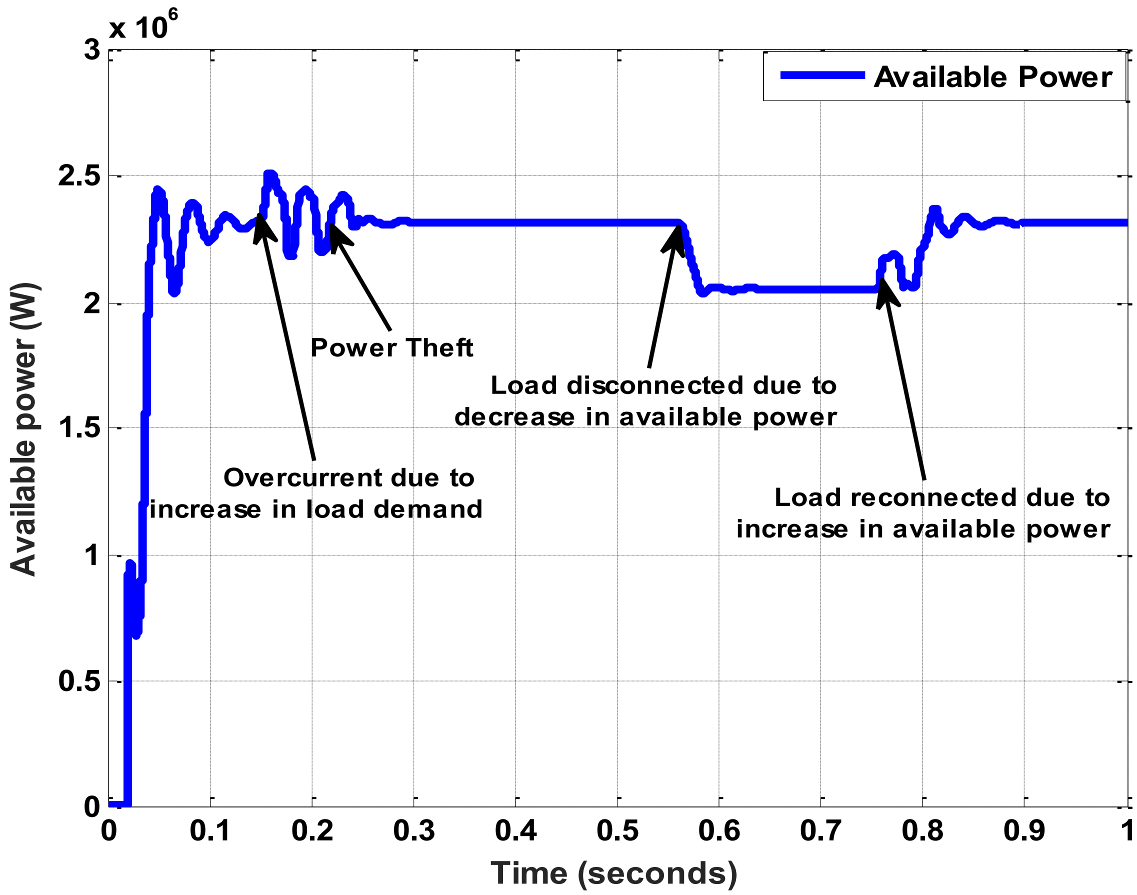

Fig. 5.23 Available power at DT_1

It has been shown from Fig. 5.23 that, the available power simulated from MATLAB/SIMULINK closely matches with the available power calculated by real-time PMU at the distribution transformer.

5.4 SUMMARY

An architecture of the distribution system has been proposed, where PMU has been placed at the main substation receiving supply from the grid through the incoming feeder, as well as at all DTs. PMU installed at the main substation is linked to master controller (secondary controller) through IEC-61850 communication protocol. PMUs placed at DTs are connected to the corresponding local controller (primary controller) through the IEC-61850 communication protocol. Estimated voltage and current phasors together with frequency are transmitted from PMU to the local controller through IEC-61850 communication protocol. Controllers perform different tasks based on the data received from PMUs. PMU Measurements has been used in real-time computation of available power at the substation and load disconnection/reconnection based on it. PMU measurements have been used further in real-time estimation and control of overcurrent through feeder and power theft detection and removal. Simulation results obtained through eMEGASim® OP5600 OPAL-RT real-time simulator establish the effectiveness of PMU measurements in automatic monitoring, control and protection of distribution networks.