PMU and DVR based Power System Monitoring, Controlling and Voltage sag Compensation.

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Abstract: The power system network is becoming dense and much more complex. Dynamic and continuous monitoring of the power system network is required to avoid power outages. Phasor Measurement Unit (PMU) is one such device that provides state estimation parameters of dynamic power system networks that are used for designing relays and controlling the system network. Power Quality problems such as voltage sags and swells can damage the sensitive load and cause abnormal voltage, current, and frequency conditions in a power system network. Fast and major developments in power electronics technology have made it possible to mitigate the power quality problems. Dynamic Voltage Restorer (DVR) is a voltage sag compensation device that compensates the difference in voltage avoiding interruptions and restores the voltage to the pre-fault value. This paper discusses a technique used for monitoring, protecting, and controlling the system under fault condition using PMU and compensate voltage sag for a sensitive load using DVR based on the data collected by placing PMU in an optimal location. The outcome of the above analysis is recorded which shows that effective monitoring, controlling, and voltage sag compensation can be done with less number of PMU's placed optimally in conjunction with DVR.

Keywords: PMU, DVR, Optimal Location, voltage sag.

1. Introduction

Power System outages in large power transmission lines have become more frequent and are subjected to transmission line faults at every instant. Faults can be defined as undesirable and unavoidable incidents that can disturb the stable condition of the power system network. Due to factors such as the detection of faults and abnormal conditions, there is a need for constant monitoring of power system networks [1]. Phasor Measurement Units (PMU) is a controlling and monitoring device that consistently monitors the power system network and controls the operation of circuit breakers by designing a protective relaying scheme [2]. The installation of PMU in a power system network is not feasible due to the high installation cost, the use of high precision sensors, and the development of phasor data centers. The use of PMU must be such that it should provide monitoring and controlling of the entire power system network with full observability and using the least number of PMU [3].

Power Quality problems like voltage sags, swells, dips, and harmonics create problems for both end-user customer and electrical utility. The power quality problems can be rectified using Flexible Alternating Current Transmission System (FACTS) devices. Dynamic Voltage Restorer (DVR) is a power electronic device from the FACTS family that protects the sensitive load from various disturbances in the power supply. The basic principle of DVR is to detect the voltage sag and restore the difference in voltage of desired magnitude and frequency. The advantage of DVR is that it compensates voltage sag of sensitive load with a fault current limiting capacity [4]. In a three-phase system, DVR compensates the difference in voltage with desired magnitude, frequency, and phase angle in synchronism to reshape the voltage waveform. In the distribution system, the amplitude and phase angle of the injected voltage is variable allowing the control of real and reactive power exchange, leading to improving the efficiency of the system and protecting the grid from tripping. [5]- [6].

Constant monitoring of the power system is required for the control of FACTS devices [7]. FACTS devices (thyristor based) in conjunction with PMU provides a compatible solution for uninterrupted power supply. PMU monitors the power supply network and provides data required for protection as well as it provides the state estimation parameters required for the operation of FACTS devices.[8]. Implementation of FACTS devices using the thyristor-based technique is complex, whereas implementation using MOSFET is simple in operation. Hence, in this paper an attempt has been made to implement PMU in conjunction with (MOSFET based) DVR for monitoring, controlling, and voltage sag compensation for a sensitive load. It is not advisable to place PMU on every bus.

Also, an IEEE 5 BUS System is monitored, controlled, and protected from transmission line faults by placing PMUs in optimal places. To observe the whole system, the optimal location of PMU is obtained through an Integer Programming based method. PMU data are used for fault detection and protection of transmission lines. DVR is implemented for the IEEE 5 BUS system network where it compensates the voltage sag of a sensitive load. The data obtained from PMUs are used for DVR operation.

The paper is organized as follows, In Section 2 Optimal Placement of PMU methodology is explained. Section 3 gives a brief introduction to the DVR. Section 4 includes the case study performed in MATLAB/Simulink. The paper is concluded in Section 5 and References are listed.

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2. Optimal Placement of PMU

Phasor Measurement Units provide two types of measurement; they are branch voltage phasors and branch current phasors. Installation Cost of PMU is high due to the setup of Phasor Data Centres (PDC) for controlling the transmission line remotely where the phasors are synchronized with Global Positioning System (GPS). For a wide-area measurement system (WAMS) placing PMU at every bus is not possible, hence the objective of the PMU placement problem is to render an observable system by using a minimum number of PMUs. The Optimal PMU placement problem is solved using Integer Programming based procedure. Using the numerical based method of Integer Programming based Procedure the Optimal Placement Problem is formulated [9]- [10]

For an n-bus system, the PMU placement problem can be formulated as follows:

$$f(x) = \Sigma_{k=1}^{N} x(k) \quad (1)$$
$$=1$$

subject to $\lfloor A \rfloor * \lfloor X \rfloor \geq \lfloor b \rfloor$

where N is a number of system buses and $\lfloor A \rfloor$ is admittance matrix. Entries for Matrix $\lfloor A \rfloor$ is derived as follows:

$$[A] = \begin{cases} 1\ if\ i = j \\ 1\ if\ i\ and\ j\ are\ connected \\ 0\ if\ otherwise \end{cases} \quad (2)$$

In equation (1), $f(x)$ is the vector function that gives the optimal number of PMU's to be used. $\lfloor X \rfloor$ is defined as a binary decision variable vector where $\lfloor X \rfloor = \lfloor x_1 x_2 x_3 x_4 \ldots xn \rfloor\ T$

$$xi = \begin{cases} 1\ if\ PMU\ is\ installed\ at\ bus\ i \\ 0\ otherwise \end{cases} \quad (3)$$

$\lfloor b \rfloor$ is a column vector where Matrix $\lfloor b \rfloor = \lfloor 1\ 1\ 1\ 1 \ldots 1 \rfloor^{T} 1 * N$

Using the admittance matrix, the optimal placement of PMU is derived. The procedure followed for calculating the bus admittance matrix is such that, the bus that has a PMU installed provides voltage and current phasor of all the buses that are connected to it using Ohm's law. Zero injection bus (ZIB) are those buses that do not have any generation or load across it. When PMU is incident to an observable ZIB, all buses are observable. Then, an unobservable system is identified by applying Kirchhoff's Current Law (KCL) at the ZIB. When PMU is placed for an unobservable ZIB, the ZIB will be identified as observable by applying the node equation. The procedure of developing the constraint functions are carried out for two possible cases in the power system network are:

1. A System with no Conventional Measurements

In this case, the ZIB buses are ignored by the test system. Initially for obtaining the constraint set of the system network the bus admittance matrix A is formed such that entries in the admittance matrix are in the form of binary form as mentioned in equation 1 and 2.

2. System with Zero Injection Bus

Zero Injection Bus (ZIB) doesn't have any generation or load unit. For ZIB in a power system network, the current phasor of all the buses can be obtained using Kirchhoff's Current Law. This reduces the number of PMUs in every case. The ZIB method is mostly used for the distribution system where voltage injection is done to the grid. Hence, a Power System Network which has Zero Injection Bus reduces the complexity in designing the admittance matrix and also reduces the number of PMUs to be placed.

A case study is performed for obtaining the optimal location of PMU for an IEEE 5 Bus System.

3. Dynamic Voltage Restorer

DVR is a compensation device used for compensating voltage sag for sensitive load where the demand for voltage is high [11]. The location of DVR is near to the load as shown in Fig.1. The components of DVR are Direct Current (DC) voltage Source, Voltage Source Inverter (VSI), DVR Control Unit, Injection Transformer, and Filters. The Control Unit of DVR detects the voltage sag and injects the difference in voltage using VSI and Injection Transformer. DVR remains in standby mode when no voltage sag is detected and is in active mode after the detection of voltage sag. The control of DVR is shown in Fig.2. The three-phase voltage of the transmission line Vsa, Vsb, and Vsc are compared continuously with a three-phase reference voltage Vra, Vrb, and Vrc to detect the voltage sag condition [11]. The Phase-Locked Loop (PLL) method is implemented to calculate phase angle, frequency, and amplitude of voltage using the Synchronous Reference Frame (SRF) theory. The advantage of using SRF theory is that it is easy to detect voltage sag of a dynamic system in a rotating reference frame and easy to implement and control reactive power flow. After detecting the voltage sag in the rotating reference frame, it is converted to the a-b-c reference frame to calculate the voltage sag.

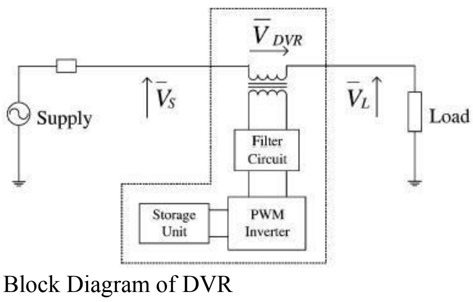

Fig.1. Block Diagram of DVR

The detected sag voltage in the a-b-c reference frame is used to generate the pulses for VSI. VSI is

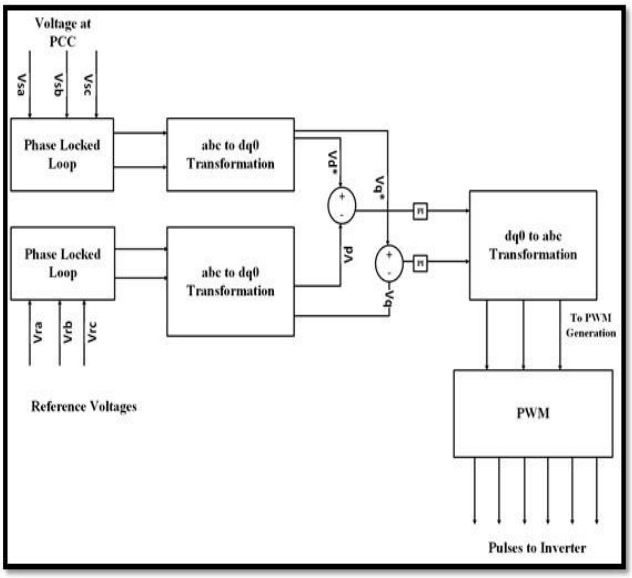

Fig.2 Control System of DVR

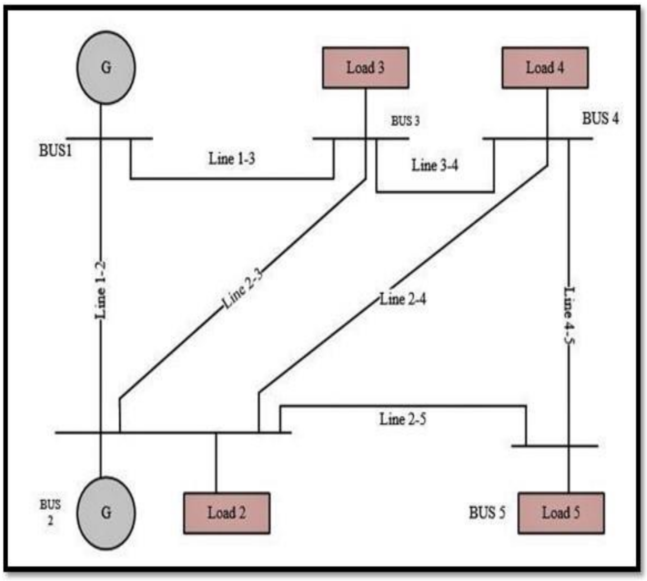

Fig.3 IEEE 5 BUS System

driven using the Sinusoidal Pulse Width Modulation technique where the pulses are generated by comparing the voltage sag sine wave with the high switching frequency wave [12]-[13]. The produced voltage is filtered out using an LC filter eliminating the harmonics and providing a smooth sinusoidal waveform. The produced difference in voltage is injected into the transmission line using injection transformers.

4. Monitoring using PMU and compensation using DVR

The case study is performed in MATLAB/Simulink for three cases.

Case1: Optimal Placement of PMU using Integer Programming based Method
Case2: Monitoring of entire IEEE 5 BUS System using PMU
Case3: Monitoring, controlling, and compensating voltage sag using PMU and DVR for one load.

Case1: The optimal placement of PMU is tested in an IEEE 5 Bus System as shown in Fig3. The Standard IEEE 5 Bus System is as follows:

1. The total number of buses are 5.
2. Two three-phase voltage sources DG1 and DG2 are placed at BUS1 and BUS2 that supply power to four loads placed at BUS2, BUS3, BUS4, and BUS5 respectively. The load at BUS5 is sensitive as mentioned in the Appendix.
3. DG1 and DG2 form a distribution network of 7.9kV which is supplying power to four identical types of load forms a ring distribution network as mentioned in the Appendix.
4. There are seven transmission lines and they are interconnected to the buses as Line 1-2, Line 2-3, Line 2-4, Line 2-5, Line 4-5, Line 3-4, and Line 1-3.

The Optimal Placement problem of PMU for the IEEE 5 Bus system is resolved using Integer Programming based Method.

At BUS1 if a voltage measurement block is placed, it will observe the voltage and current measurements radially of BUS 2 and BUS 3. So, if PMU is placed at BUS1 it provides the state estimation of BUS1, BUS2, and BUS3.

Similarly, if a Voltage measurement block is placed at BUS 3, it will observe the voltage and current ratings of BUS 1, BUS 2, BUS 3 and BUS 4

As mentioned in equation (1), (2) and (3), The Bus Admittance Matrix A for IEEE 5 Bus System is written as

$$A = \begin{pmatrix} 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 \end{pmatrix} \quad (4)$$

The constraints for the above case are formed as,

$$\begin{cases} f1 = x1 + x2 + x3 & \geq 1 \\ f2 \ = x1 + x2 + x3 + x4 + x5 & \geq 1 \\ f3 = x1 + x2 + x3 + x4 & \geq 1 \\ f4 = x2 + x3 + x4 + x5 & \geq 1 \\ f5 = x2 + x4 + x5 & \geq 1 \end{cases} \quad (5)$$

The operator '+' is the logical OR Operator the use of 1 on the right-hand side of the inequality ensures that at least one of the variables appearing in the sum will be non-zero. The first constraint $f1 \geq 1$ implies that one PMU must be placed at either of the buses 1,2 and 3 to make bus 1 observable. Similarly, for the second constraint $f2 \geq 1$ implies that PMU must be placed either of the buses 1,2,3,4 and 5 to make bus 2 observable. The IEEE 5 Bus System is shown in Fig.3

The Optimization of selecting the Placement of PMU is done such that, from the admittance matrix, the BUS which contains more number of binary 1s in its row is selected as an optimal placement where the system is completely observable. Hence for a Standard IEEE 5

Bus system single, PMU is placed at BUS 2(as observed from the matrix). The solution for IEEE 5 Bus system is tabulated in Table 1,

Table1 Solution for Optimal Placement Problem

System	No. of Branches	No. of PMU's	Location of PMU's
IEEE 5 BUS	7	1	Bus 2

Case2: Monitoring of entire IEEE 5 BUS System using PMU

The objective of the case study is to monitor the IEEE 5 BUS System from an optimized location of PMU. The data collected are used for:

1. Voltage sag compensation of sensitive load at BUS 5 using DVR.
2. Protection of BUS 4 from transmission line fault using PMU based impedance relay.

Observation of Case2:

The IEEE 5 BUS designed in MATLAB/Simulink is implemented as shown in Fig3. During normal conditions, the PMU at BUS 2 shows the voltage ratings as 7.07kV and current rating as 0.27A. The waveforms are shown in Fig.4 and Fig.5

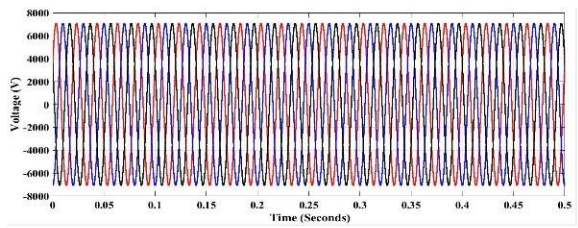

Fig.4 Voltage reading recorded by PMU from BUS2

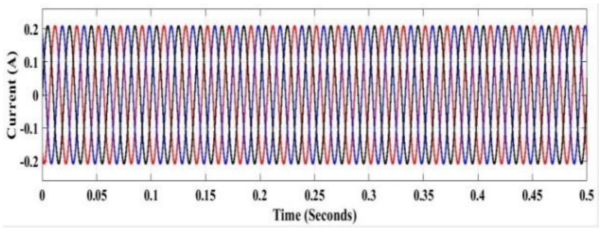

Fig.5 Current reading recorded by PMU from BUS2

The Positive sequence voltage recorded by PMU at BUS2 during normal condition was observed to be 7.07kV as shown in Fig. 6.

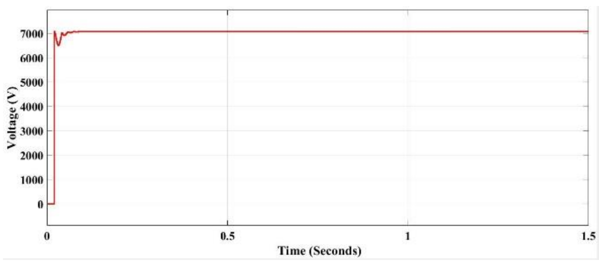

Fig.6 Positive Sequence voltage recorded by PMU from bus2

The Positive Sequence current observed by PMU at Bus 2 during normal condition is 0.2A as shown in Fig.7.

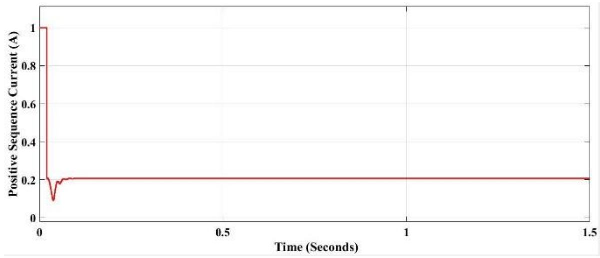

Fig.7 Positive Sequence current recorded by PMU from bus2

The impedance reading of PMU observed is 33460 ohms. The waveform is shown in Fig.8.

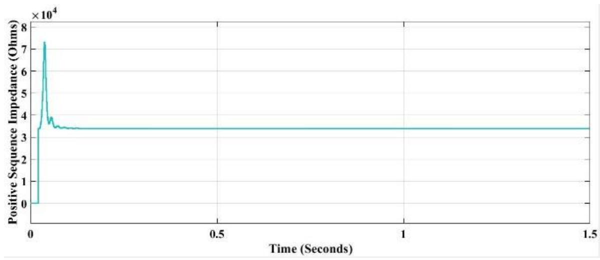

Fig.8 Impedance waveform recorded by PMU from BUS2

Case3 (a): In case3 (a), transmission line fault detection using optimized PMU location for an IEEE 5 BUS System was simulated in MATLAB/Simulink as shown in Fig 9.

In this case study for an IEEE 5 BUS system, a three-phase fault is generated at every transmission line for a specific time and the system is observed. The voltage and current readings recorded by PMU from BUS 2 are tabulated in Table 2.

Table 2 Reading recorded by PMU during faults from BUS2

Transmission Line Number	Fault Time	Voltage Readings (V)	Current Readings (A)
Line 1-2	0.1 to 0.2 sec	V1=1.9 V2=1.8 V3=-1.7	I1=828A I2=796A I3=792A
Line 1-3	0.3 to 0.4sec	V1=6.2kV V2=6.2kV V3=6.2kV	I1=52A I2=52A I3=52A
Line 2-3	0.5 to 0.6 sec	V1=6.2kV V2=6.2kV V3=6.2kV	I1=52A I2=52A I3=52A
Line 2-4	0.7 to 0.8 sec	V1=6.15kV V2=6.15kV V3=6.15kV	I1=60A I2=60A I3=60A
Line 2-5	0.9 to 1 sec	V1=1.8V V2=1.8V V3=1.7V	I1=314A I2=314A I3=314A
Line 3-4	1.1 to 1.2 sec	V1=6.2kV V2=6.2kV V3=6.2kV	I1=52A I2=52A I3=52A
Line 4-5	1.3 to 1.4 sec	V1=6.15kV V2=6.15kV V3=6.15kV	I1=60A I2=60A I3=60A

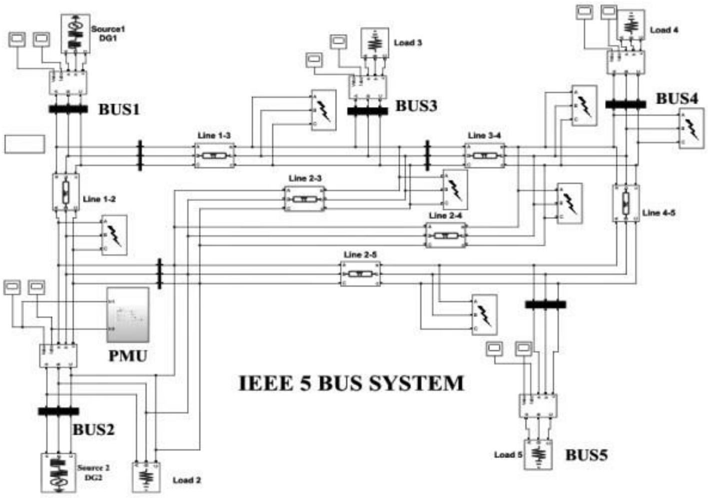

Fig.9 Transmission line fault detection using PMU

As mentioned in Table 2, PMU detects a fall in voltage ratings during the fault generated time at every transmission line. The entire system is observable with a single PMU placed at BUS 2 and the voltage waveform observed from the optimal location is shown in Fig.10.

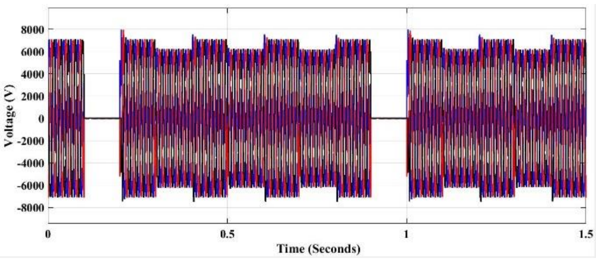

Fig.10 Voltage waveform recorded by PMU from BUS2

PMU detects the rise in current ratings from a nominal range of 0.2A whenever a fault is generated which is shown in Fig 11.

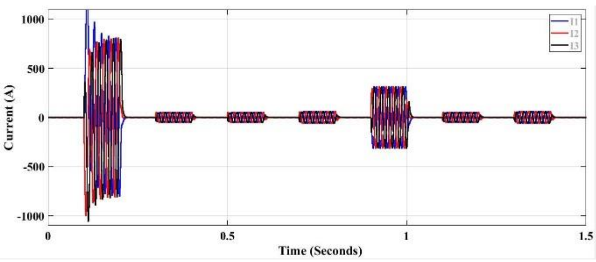

Fig.11 Current waveform recorded by PMU from Bus2

Positive sequence voltage, positive sequence current, and impedance readings recorded by PMU during fault conditions are tabulated in Table 3.

The Circuit breaker is placed on transmission line 3-4 for protection of Load at BUS4. The logic operation of the circuit breaker is designed in such a manner that whenever the impedance value goes below 2000 Ω PMU senses the fault and the impedance relay gives the trip signal command to the circuit breaker. The load connected to the faulty transmission line is isolated after detecting the fault.

Case 3(b): Monitoring, Controlling and voltage sag compensation of a sensitive load in an IEEE 5 BUS System

For an IEEE 5 BUS System, the three-phase fault is generated at bus 4 on transmission lines 3-4 for a period of 0.3 seconds from 0.3 to 0.6 seconds causing voltage sag at Bus 5. The objective of this case study is to isolate the Bus 4 during fault conditions by sensing the fault conditions and simultaneously compensating voltage sag at BUS 5 using DVR.

Table 3 Sequence Voltage, Current Readings, and Impedance recorded by PMU

Transmission Line Number	Fault Time	Positive Sequence Voltage Readings (V)	Positive Sequence Current Readings (A)	Impedance
Line 1-2	0.1to 0.2 sec	1.7 V	828A	0.002
Line 1-3	0.3 to 0.4sec	6.2kV	52A	117
Line 2-3	0.5 to 0.6 sec	6.2kV	52A	117
Line 2-4	0.7 to 0.8 sec	6.15kV	60A	101
Line 2-5	0.9 to 1 sec	1.7V	314A	0.005
Line 3-4	1.1 to 1.2 sec	6.2kV	52A	117
Line 4-5	1.3 to 1.4 sec	6.15kV	60A	101

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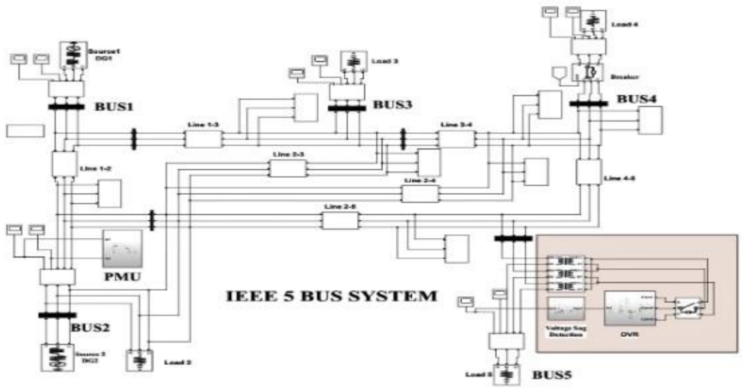

Fig12 IEEE 5 Bus System in MATLAB/Simulink

DVR is connected between BUS 4 and BUS 5. Since a three-phase fault is generated on transmission lines 3-4 which leads to voltage sag condition at BUS 5 which is a sensitive load. The block diagram of the above case study is shown in Fig. 12.

Table 4 DVR Parameters for case study 4

Block	Parameters
DC-Link Voltage	5070V
Fault Time	0.3 to 0.6 Sec
Injection Transformer ratio	1:1
PWM Inverter (SPWM)	6 Pulses 2kHz
Controller	Vector Control
Fault Location	BUS 4 Transmission line 3-4
DVR Location	At BUS 5

During the normal condition, the voltage rating is 7.07kV, and the current is 0.2A. During fault time, the PMU records drop in voltage as 6.2kV and increase in current as 60A which are the positive sequence voltage and positive sequence current. The voltage observed at Bus 2 by PMU is 6.2 kV is shown in Fig.13.

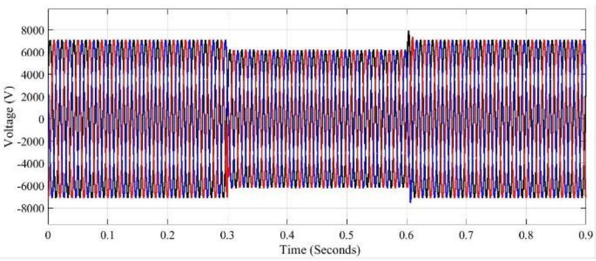

Fig.13 Voltage reading observed during fault conditions

The expanded waveform of voltage rating is shown in Fig 14.

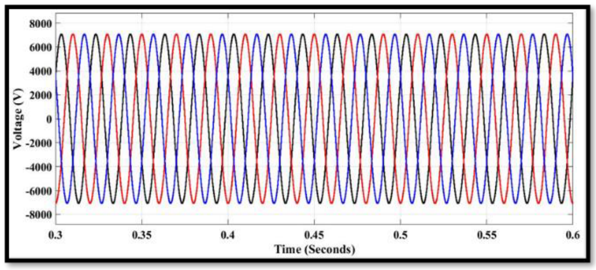

Fig14 Expanded Voltage Waveform

The current observed form Bus 2 by PMU is 60 A as shown in Fig15.

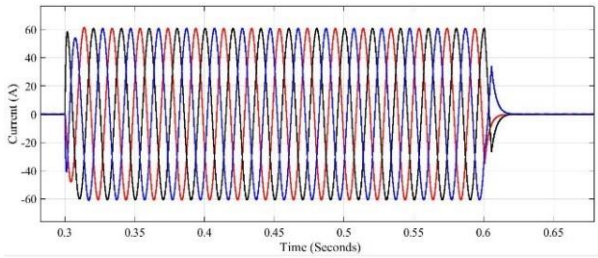

Fig.15 Current reading observed during the fault condition

The Positive Sequence Impedance during normal conditions is 33460 Ω which falls to 100 Ω during fault time.

For BUS 4, The Impedance relay is designed such that whenever the impedance falls below 33000 Ω the breaker trips. For safer limits, the value is considered as 20000 Ω where a trip signal is generated by PMU for the tripping of the circuit breaker.

The Circuit breaker at BUS 4 trips at 0.3 seconds isolating the load at BUS 5. The Current waveform of BUS 4 is shown in Fig.16.

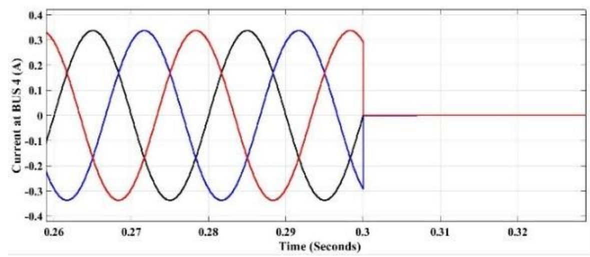

Fig.16 Breaker trips at BUS4

The Voltage Sag Compensation of Load 5 placed at BUS 5 is such that, during normal condition the voltage is 7.07kV and during fault for a period 0.3 to 0.6 sec it goes down to 4.11kV. as shown in Fig. 17.

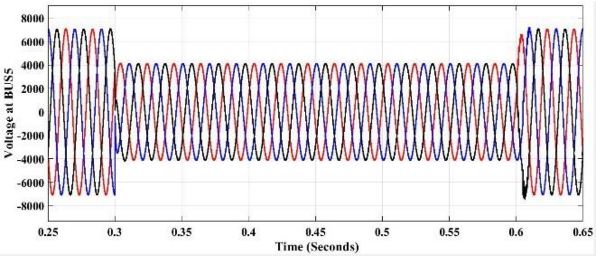

Fig.17 Voltage sag detected at BUS5

The DVR injects the difference of 2.96kV voltage into the system using Injection transformer. The Voltage at BUS5 after injection of Voltage into the system is shown in Fig.18.

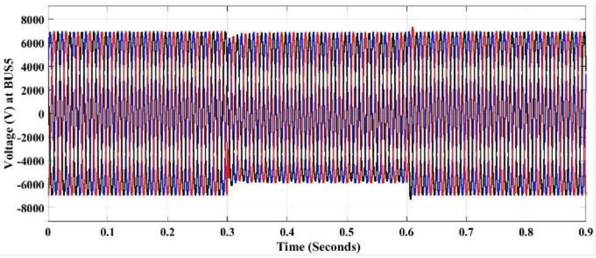

Fig.18 Voltage Sag compensated at BUS5

The faulty transmission line 3-4 is isolated at 0.3 secs, DVR compensates the voltage sag observed at load 5 due to fault at transmission line 3-4 between 0.3 to 0.6 seconds as shown in Fig 18.

5. Conclusion

PMU is used as a monitoring and controlling device for the detection of faults and protection. The above work has been carried out by considering the optimal location of PMU for an IEEE 5 BUS System. By using Integer Programming based Method the optimal location for placing PMU was obtained to be BUS 2. Several case studies have been discussed in this paper to show that a single PMU can monitor the whole system efficiently. Results have been recorded for monitoring and controlling the full system when a three-phase fault occurs, From the results, it is observed that data from a single PMU at BUS 2 is sufficient to monitor, protect and also compensate the voltage sag for a sensitive load. The MOSFET-based FACTS device (DVR) was implemented for voltage sag compensation using the data collected through PMU's. The case study performed shows that PMU in conjunction with DVR was found to be simple and easy to detect the voltage sag. It can be concluded that a power system network can be monitored, controlled, and protected using less number of PMU's. Various voltage sag compensation techniques can be implemented using PMU data for improving reliability.

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Appendix

Abbreviation

MOSFET: Metal Oxide Semi-Conductor Field Effect Transistor

IEEE 5 BUS System Parameter

The sensitive load is placed at BUS 5. The Parameters of Load and Three-phase source used in IEEE 5 Bus System is mentioned in Table 1

Table 1 Parameters in IEEE 5 BUS System

Bus Code	Assumed Bus Voltage	Generation		Load	
		Watts	vars	Watts	vars
1	5 kV	$3.9*10^3$	0	0	0
2	5 kV	$9.65*10^2$	0	0	0
3	0	0	0	$1.54*10^3$	0
4	0	0	0	$1.5*10^3$	0
5	0	0	0	$-1.5*10^3$	0

The Bus type, Initial Voltage, and angle of IEEE 5 BUS Network is shown in Table 2

Table 2 Bus Type. Initial Voltage of IEEE 5 BUS System

BUS No	1	2	3	4	5
BUS Type	PV	PV	Constant Z	Constant Z	Constant Z
Initial Voltage (Per Unit)	1	1	1	1	1
Initial Voltage Angle	0	0	0	0	0

Transmission Line Parameter is tabulated in Table 3 and Table 4

Table 3 Transmission Line Parameter of IEEE 5 BUS System per unit value

From BUS	To BUS	Transmission Line resistance	Transmission Line Reactance	Transmission line Conductance	Transmission Line Susceptance
1	2	0.02	0.06	0	0.06
1	3	0.08	0.24	0	0.05
2	3	0.06	0.18	0	0.04
2	4	0.06	0.18	0	0.04
2	5	0.04	0.12	0	0.03
3	4	0.01	0.03	0	0.02
4	5	0.08	0.24	0	0.05

Table 4 Length of Transmission Line

BUS	Length Of transmission Line
1-2	47
1-3	87
2-3	67
2-4	67
2-5	47
3-4	19
4-5	87