



**Article Title: Distribution System Protection with PV Plants Using Q-Axis Components**

## **Distribution System Protection with PV Plants Using Q-Axis Components**

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### **ABSTRACT**

Satisfying fault ride-through requirements, solar photovoltaic (PV) plant remains connected to the grid even during a fault. With the current limiting feature, the plant current during a fault becomes comparable to its rated current. This imposes challenges to conventional local data-based protection methods employed in the relay on PV side. In such a situation, the selectivity of a protection scheme is crucial for maintaining an uninterrupted supply to customers. In this article, a q-axis component-based protection scheme is proposed for the distribution system with a PV plant. The method extracts the second-order harmonic components of q-axis voltage and current at relaying points for fault detection and direction identification. Using this direction information at both ends of a line segment is protected, internal and external faults are discriminated. The performance of the proposed method is tested on a 14-bus distribution system for various fault cases. A comparative analysis with existing techniques shows the strength of the proposed method. Hardware-in loop testing using OPAL-RT simulator as a system and Arduino NANO microcontroller as relay validates the performance of the proposed method in real-time.

### **1 Introduction**

Today a massive growth in solar photovoltaic (PV) plant has been observed worldwide due to the depletion of fossil fuels and environmental concern. Such a plant is connected to a distribution system through a power electronic inverter. During a fault in the system, the inverter allows limited current for its protection. As a result, fault current seen by the relay on PV-side of the line connecting PV plant to the grid becomes comparable to rated current, and fault detection using the magnitude of current is difficult in such a system. Further, the control strategy in the inverter controller causes leading power factor of PV output current during a fault, whereas, it is lagging for conventional system. This limits the application of conventional angle-based directional principle. For these reasons, the performance of the available protection scheme is restricted while protecting PV-integrated distribution system.

For high fault resistance and with associated voltage control strategy in the PV plant, the faulted phase voltage can be higher than the threshold, which limits the performance of such relay. A voltage-restrained overcurrent relay is proposed in using phase voltage and phase current for fixing the required threshold. However, control strategy in the PV plant can create phase



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currents higher in magnitude in a healthy phase than a faulted phase resulting in incorrect operation of the relay. Therefore, phase quantities-based technique is not suitable for fault detection in a distribution system in the presence of a PV plant.

In a positive sequence component-based method is proposed for fault detection. Although the method is independent of the associated control strategies with controller, it fails to detect high-resistance faults. In such a situation, the transformation of three-phase signals into two signals of direct and quadrature axis components (d-q) may be a solution. In a protection technique using d-q components of voltage and current signals is proposed for fault detection. The method is able to detect only symmetrical fault during power swing and finds limitations while detecting unbalanced faults. Therefore, an alternative protection scheme is sought for protection of distribution lines in the presence of PV plant.

## **2 Methodology**

For fault ride-through requirement, solar photovoltaic (PV) plant remains connected to the grid during a fault. In such a situation, a PV plant operates in different modes and supplies current to comply with the requirements of the grid. The relative magnitude of phase current contributed by a PV plant during a fault is at par with the nominal current. Such a fault behaviour restricts the application of available phase current based relaying approaches while protecting the distribution system with a PV plant. So in order to avoid the fault in the PV system MATLAB based operating system is suitable and very effective.

### **2.1 Software Description**

#### **MATLAB**

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include Math and computation Algorithm development Data acquisition Modelling, simulation, and prototyping Data analysis, exploration, and visualization Scientific and engineering graphics Application development, including graphical user interface building MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non-interactive language such as C or FORTRAN.

##### *2.1.1 Features*

A family of add-on application-specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available



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include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others.

### *2.1.2 Modelling Dynamic Systems*

A Simulink block diagram model is a graphical representation of mathematical model of a dynamic system. A mathematical model of a dynamic system is described by a set of equations. The mathematical equations described by a block diagram model are known as algebraic, differential, and/or difference equations.

### *2.1.3 Block Diagram Semantics*

A classic block diagram consists of a dynamic system graphically consists of blocks and lines (signals). The history of these block diagram model is derived from engineering areas such as Feedback Control Theory and Signal.

A block within a block diagram defines a dynamic system in itself. The relationships between each elementary dynamic system in a block diagram are illustrated by the use of signals connecting the blocks.

Collectively the blocks and lines in a block diagram describes an overall dynamic system. Simulink extends these classic block diagram models by introducing the notion of two classes of blocks, nonvirtual block and virtual blocks. Nonvirtual blocks represent elementary systems. A virtual block is provided for graphical organizational convenience and plays no role in the definition of the system of equations described by the block diagram model.

## **2.2 Hardware Description**

### *2.2.1 Existing Sytem*

A protection method using local positive sequence voltage and current is proposed to protect a distribution system with PV plant. The method selects pickup current using proposed current-voltage curve for fault detection. A three-dimensional time-current-voltage characteristic is proposed for trip time calculation. Performance of the proposed method is tested for relays on both PV plant side and grid end using DigSilent PowerFactory simulation data for a CIGRE 14-bus distribution system with PV plant having different modes of operations. The method is found to be accurate and comparative assessment reveals its superiority.

### *2.2.2 Proposed Methodology*

This method proposes a q-axis component (QAC)-based protection scheme for distribution systems with PV plants. It is based on the principle that the output current of a PV plant and bus voltage possess significant second-order harmonic components in q-axis current and voltage during an unbalanced fault in the system. The method detects the fault using such a harmonic component in current, thereafter, computes the angle difference between second-order harmonic phasors of q-axis voltage and current to discriminate fault direction with respect

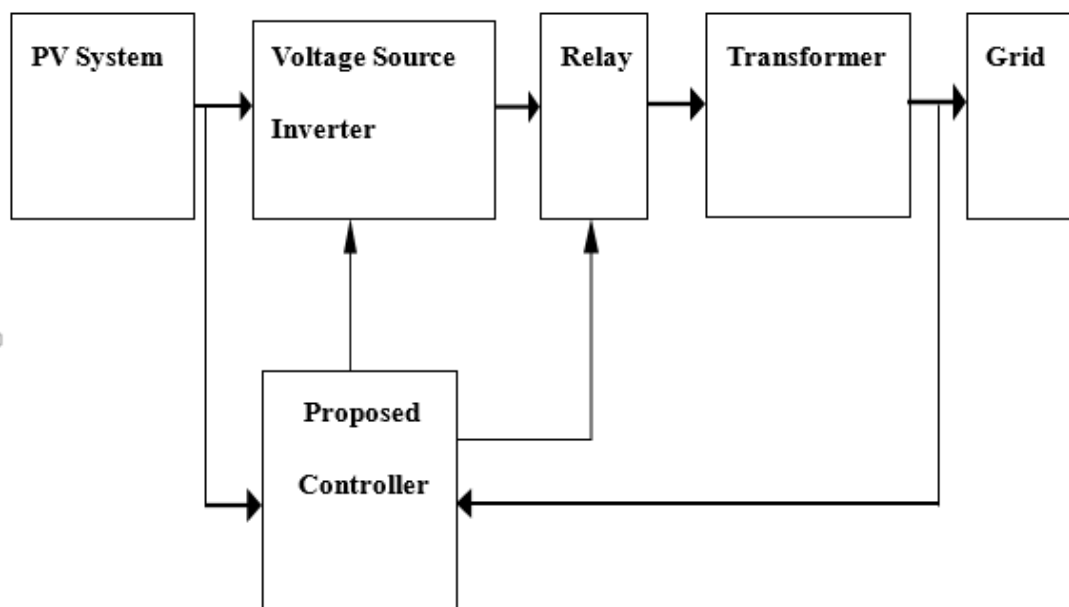


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to relay. This direction information is communicated to the other end relay of a line segment to be protected. Employing these local and other end information, each relay identifies an internal fault in a line segment. For that, first, a PV plant is modelled in dq0 domain under short-circuit condition. Then a mathematical expression ensuring the presence of a second-order harmonic component in q-axis current during an unbalanced fault in a system is derived. The performance of the proposed technique is evaluated on 14- bus distribution system with PV plant for numerous fault situations, including unbalanced faults with different fault resistances and noisy signals.

### 2.2.3 Block Diagram

During an unbalanced fault with high fault resistance in an unbalanced distribution system, the negative sequence current during prefault and fault conditions may be at par, which indicates that identification of fault direction is not possible with the existing method. Under such a fault situation, the proposed method finds  $\phi_q$  for directional relaying, which depends on the fixed q-axis impedance at the relay bus. Thus, the proposed approach is not affected by the prefault loading condition and correctly indicates the direction of high resistance fault in the system.



**Figure 1: Main Block Diagram**

### 2.3 Proposed QAC Method

The proposed QAC method uses second-order harmonic component of qaxis current and voltage for protection of distribution system with PV plant. First, a fault is detected, then the direction information is sent for selectivity. Such q components are obtained from three-phase quantities using a phase locked loop (PLL). The following subsections describes the proposed



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method and role of PLL in the proposed technique during balanced and unbalanced system conditions.

### *2.3.1 Phase-Locked Loop (PLL)*

The PLL generates an angle  $\theta$  to transform three-phase (ABC) quantities to dq variables and to adjust the rotational speed of the dq-frame such that q-axis component of voltage is forced to zero in the steady state. Under unbalanced condition, in addition to DC components, q-component of voltage includes sinusoidal components with second-order and sixth-order frequencies. Among them, the magnitude of second-order frequency is significantly high. Thus, one pair of complex-conjugate zeros of double frequency is added in the PLL compensator design to eliminate such double-frequency ripple. Such PLL design results in generation of desirable voltage and current under steady state as well as unbalanced system conditions.

### *2.3.2 Fault Detection*

PV inverter controller regulates the current at its reference value, and the error signal is compensated by proportional integral (PI) compensator. The PI compensator is unable to suppress the q-axis current oscillations at twice the nominal frequency caused by voltage imbalance during a fault. To provide the smooth operation of inverter's controller, second-order notch filter (NF) is used to remove the second-order harmonic component from the current entering into the controller whereas such second-order harmonic component remains in q-axis component of line current during an unbalanced fault. Such second-order harmonic component is used for fault detection by the proposed technique. PhaseA-to-ground fault with fault resistance  $R_F$  is created at  $F_x$ .

### *2.3.3 Selection of Faulted Section*

Followed by fault detection and direction information, a carrier-aided directional comparison scheme is used to discriminate the internal and external fault in a line segment. The operation of carrier-added directional comparison scheme shows fault at  $F_x$  in segment RN. Both relays RR and RN see the fault  $F_x$  in the forward direction and neither end receives a block signal (i.e., 0) from remote ends through the pilot protection scheme. As a result, a trip (i.e., 1) is generated by the relays for isolation of faulted line segment RN, with the available measurements at relay bus R, second-order harmonic components of q-axis voltage and current signals are measured.

## **3 Result Analysis**

This research is implemented in the software of MATLAB simulation Language. The effectiveness of the proposed control method has been investigated on MATLAB Simulation.



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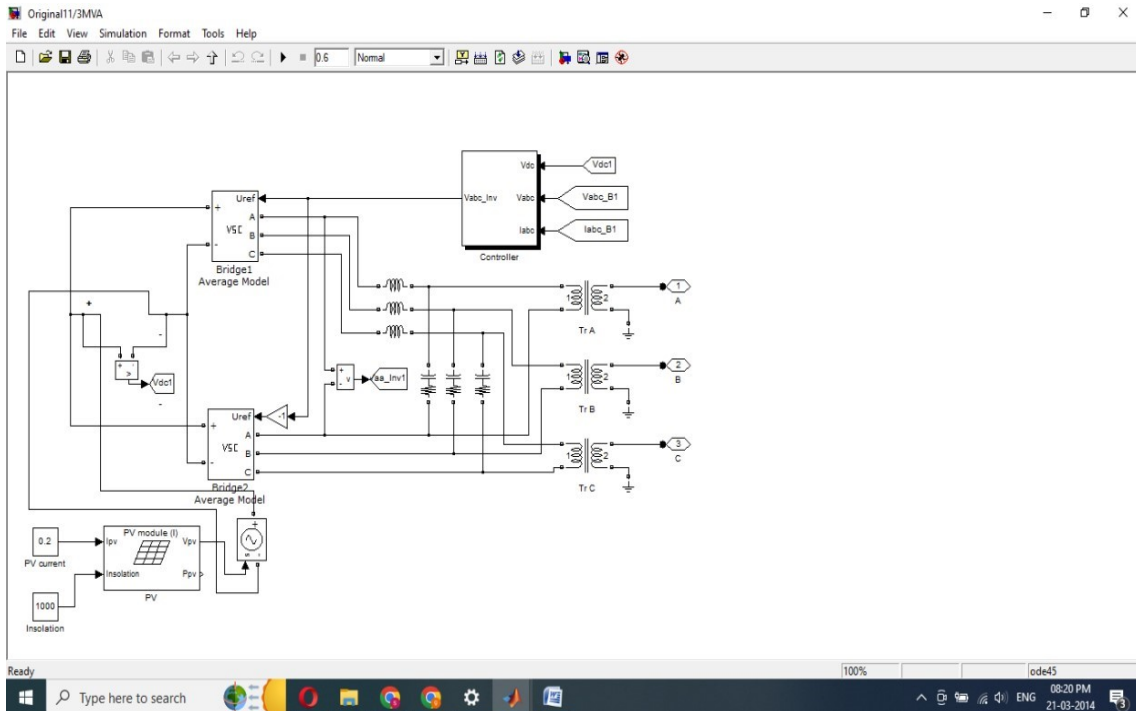
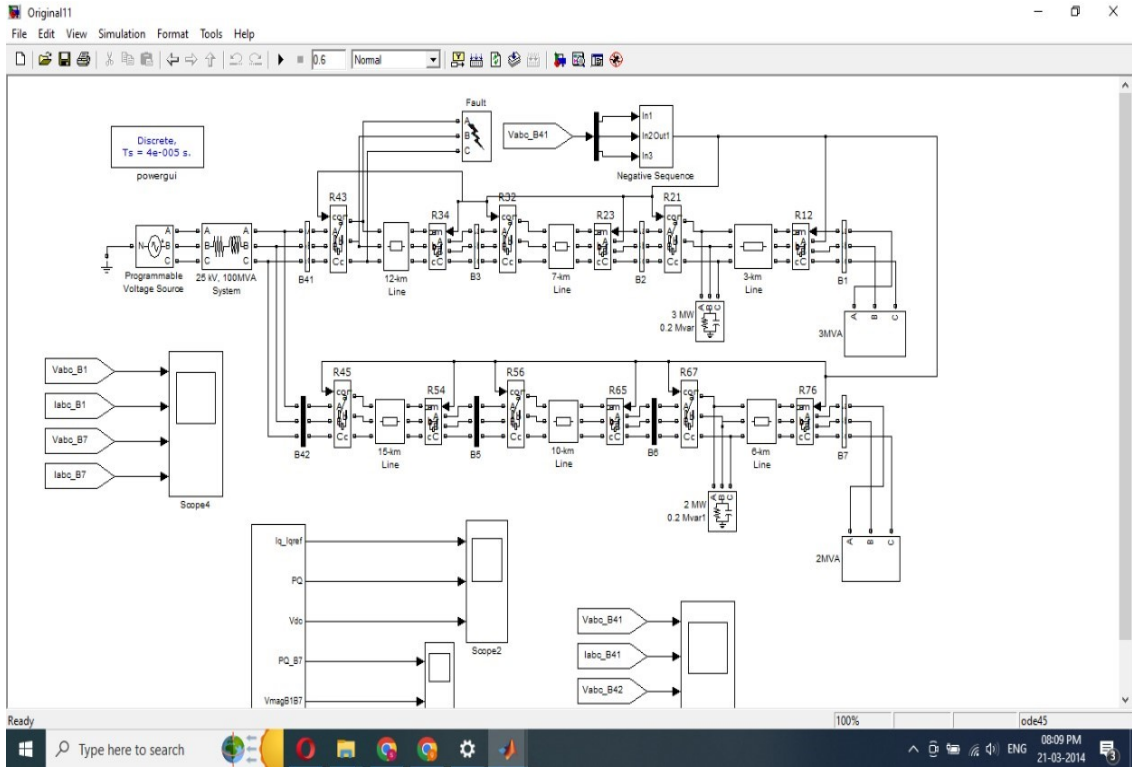
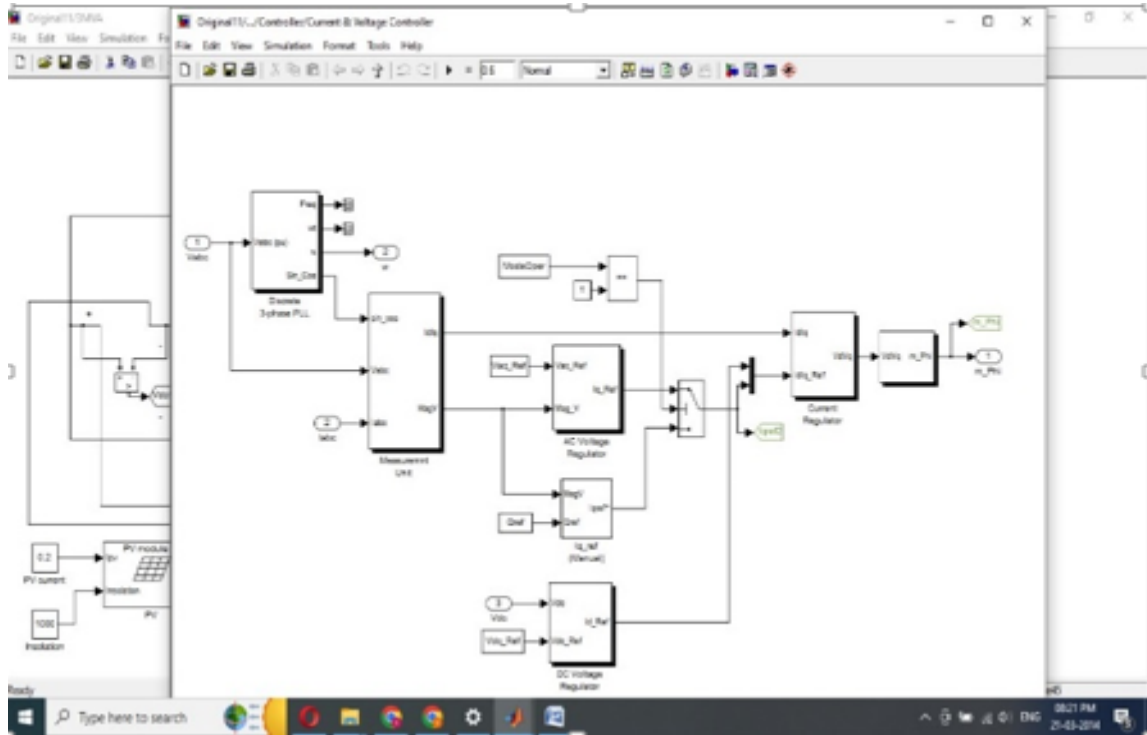


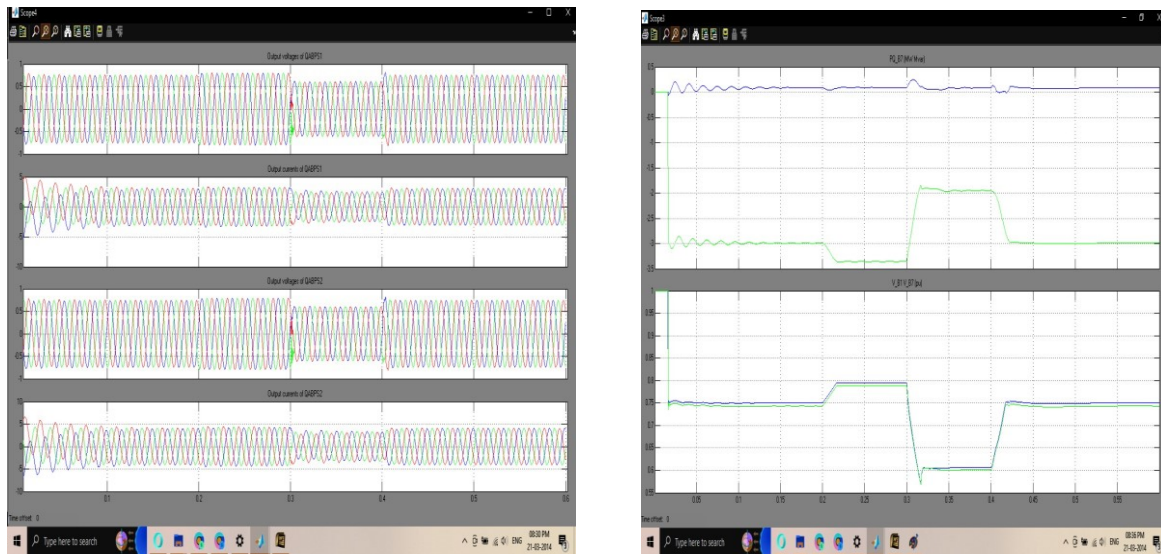
Figure 2: Bus System with PV model and Inverter model



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**Figure 3: Proposed Controller design**



**Figure 4: Relay controlled Bus Voltage and current and Active, Reactive power and Voltage Magnitude under fault**



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#### 4 Conclusion

This article proposes a q-axis component-based method for protection of the distribution system in the presence of an inverter-interfaced PV plant. The method uses second-order harmonic components of q-axis voltage and current at relaying point for fault detection and direction identification. This direction information is communicated to other end for confirmation of internal fault, if any, in the line segment to be protected. The performance of the proposed method is compared with conventional fault detection and direction identification techniques for different fault resistances and noisy signals in a 14-bus distribution system with the PV plants. It is observed that significant second-order harmonic component appears in q-axis current, even during high-resistance fault at the PV plant end of the line. This provides accurate improved performance compared to available methods. Moreover, with the proposed method, the angle difference for direction identification is not influenced by the control strategy in PV inverter, unlike the positive sequence component based approach. The proposed method is also verified with hardware-in-loop testing in real-time and the corresponding results confirm the applicability of the proposed method in a distribution system with PV plant.

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