Adaptive Voltage Restrained Overcurrent Relaying for Protection of Distribution System with PV Plant

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***Abstract*—With the integration of inverter based solar photovoltaic (PV) plant in the distribution system, the fault current behaviour changes significantly which limits the application of overcurrent relay (OCR) for line protection. As a solution, voltage restrained overcurrent relay (VR-OCR) can be used for line protection. The loading condition of distribution system further limits the application of VR-OCR. This work highlights the issue with existing VR-OCR scheme and proposes a protection scheme that changes the pickup settings of VR-OCR adaptively to suit the prevailing power system conditions. At a sampling rate of 1200 samples/sec for 60 Hz system, the method updates its setting at each cycle and uses it for protection decisions. Using MATLAB/Simulink, the performance of the proposed scheme is tested for various loading conditions and fault resistances in a PV connected distribution system. Hardware-in-loop testing using real-time simulator OPAL-RT and IEC 61850 communication protocol validates the proposed method in real-time application.**

***Index Terms*—Solar Photovoltaic plant, distribution system, power network protection, overcurrent relay, voltage restrained overcurrent relay, hardware-in-loop, IEC 61850.**

I. Introduction

Electric energy is one of the fundamental resources of modern industrial society. It is generated in generating stations and transmitted over long distances through high voltage transmission networks and then stepped-down to low voltage level to distribute the power to the customers by means of a distribution system. A typical distribution system is mainly protected using OCR [1]. With the integration of PV plant in the distribution system, the efficient and reliable operation of conventional OCR is very challenging task because such plant are integrated through inverters [2]. The maximum current flowing through it is limited to avoid the burning of inverter switches [3]. Thus, Fault current becomes comparable to load current and discrimination of fault from healthy condition is not possible for relay on PV-side [4], [5]. Such issue asks for a protection scheme which is independent of fault current magnitude in PV connected distribution system.

Numerous machine learning and artificial intelligence based techniques have attracted the attention of several researchers. These methods use support vector machine algorithm [6]–[8], discrete wavelet transform [9], [10], artificial neutral network [11] and combination of wavelet and neuro-fuzzy algorithm [12], [13]. A statistical method based on variance test and non-parametric kruskale-wallis test is proposed in [14]. A method using climate data from satellite observation is presented in [15]. A Learning technique is presented in [16] which categorizes the energy losses in groups. However, these techniques require massive stores of training data, and labeling these data is a tedious process.

Several adaptive overcurrent relaying techniques are proposed by researchers [17]–[23]. However, the associated control strategies in PV inverter alters the fault current pattern which limits their applicability for line protection. In such a scenario, voltage based techniques are thought of as a reliable solution. In [24], undervoltage relays are used for line protection. However, it fails with high resistance faults. In [25], voltage controlled overcurrent relay (VC-OCR) is proposed for fault detection. The method starts when the voltage magnitude is lesser than the set threshold. But, during high fault resistance, the voltage magnitude is higher than the threshold, which maloperates VC-OCR. An alternative solution is a combination of voltage and current, and VR-OCR is an attractive option [26]–[28]. VR-OCR incorporates both fault voltage as well as current for setting the threshold curve. However, the method is affected by changing loading conditions in the system.

This work proposes an adaptive setting of voltage-restrained overcurrent relay for protection of distribution line connecting solar PV plant. The method uses prefault current data available at the relay bus and input voltage for setting the trip characteristics. The performance of the proposed method is tested for various loading conditions and different fault resistances in a PV connected distribution system and found to be accurate. Hardware-in-loop testing is validated in real-time using two OPAL-RT real-time simulators and IEC 61850 communication protocol.

The rest of this paper is organized as follows. In Section II, the working principle of VR-OCR is discussed. In Section III, the issue with VR-OCR in the presence of PV plant is discussed. In Section IV, the proposed method is provided. The performance of proposed method is evaluated using simulated data in Section V and using real-time test signals in Section VI. Finally, in Section VII, the work is concluded.

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II. Working Principle of VR-OCR

VR-OCR is used to protect the distribution lines using voltage and current. The pickup current (I_{pickup}) of the relay is a function of fault voltage (V), as shown in Fig. 1. The pickup current is 100% of maximum pickup current at rated voltage. From 1 p.u. to 0.25 p.u., the pickup current decreases proportionally with voltage. Below 0.25 p.u. voltage, 25% of maximum pickup current is required to operate the relay [29]. Typically, the maximum pickup current is taken as 110% of rated load current in a distribution system [1]. Therefore, current values are selected as 0.275 p.u. and 1.1 p.u. at 0 p.u. and 1.0 p.u. voltages, respectively. If the magnitude of fault current is greater than the threshold for a fault voltage, relay sends a trip command; otherwise, block.

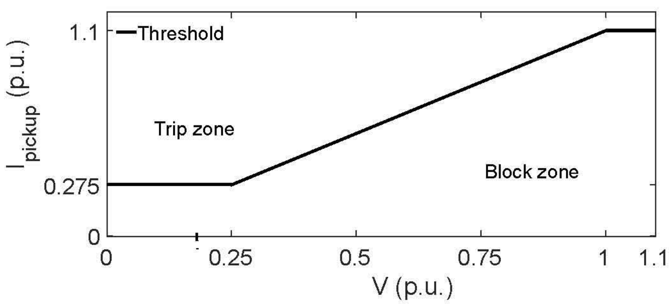

Fig. 1: Conventional tripping characteristics of VR-OCR.

III. Issue with VR-OCR

A three-bus 4.16 kV, 60 Hz distribution system with 1 MW PV plant connected at bus M is shown in Fig. 2. A load is connected at bus M. Line segments MR and RN have same length. The detailed system data for simulation is given in Appendix A. Nominal power-flow direction is from PV plant (bus M) to grid (bus N). A voltage restrained overcurrent relay R_R with tripping characteristics, as shown in Fig. 1, is used to protect the line segment RN against the fault at F.

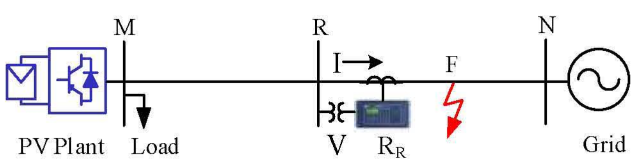

Fig. 2: A PV plant integrated three-bus distribution system.

Fault cases are simulated. A load with various loading conditions ranging from 0% to 100% loading as per base value of 1 MVA for 4.16 kV system is considered. Phase-A-to-ground fault with 10 Ω fault resistance is created at a distance of 50% from bus R at F. Results are shown in Fig. 3. It is observed that the existing VR-OCR characteristics identifies the fault correctly for 0% loading condition, whereas it fails with increase in loading condition to 50% and 100%. Because, PV plant supplies a limit current to avoid the burning of switches of PV inverter. With the increase in loading, fault

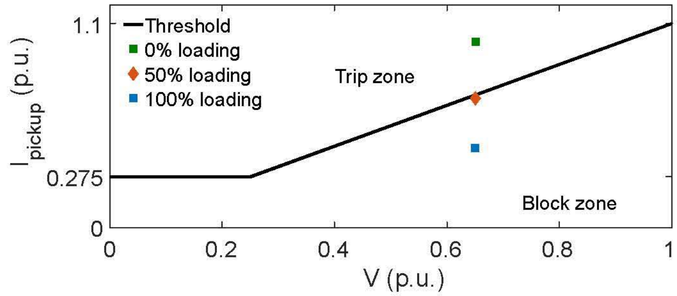

Fig. 3: Voltage and current seen by R_R during phase-A-to-ground fault at 0%, 50% and 100% loading conditions.

current seen by the relay decreases at the same fault resistance, resulting voltage and current relation in block zone. It depicts that prefault loading condition or prefault current seen by the relay influences the performance of existing VR-OCR for line protection. Thus, a method is needed to update its pickup current setting adaptively in accordance with the change in operating condition of distribution system in presence of PV plant.

IV. Proposed Adaptive Characteristics for VR-OCR

An adaptive VR-OCR characteristics is proposed to protect the distribution line connecting inverter-interfaced PV plant. The method utilizes the input voltage magnitude to change the tripping characteristics adaptively in accordance with the prefault current seen by the relay. The proposed adaptive pickup current can be expressed as,

$$I_{pickup\_new} = I_{pre}\ e^{V-1} \tag{1}$$

where I_{pre} is prefault current seen by the relay and input voltage V varies from 0 to 1 p.u.

The proposed characteristics in (1) consists of two parts. The first part is the prefault current seen by the relay. This part ensures the change in trip characteristics adaptively in accordance with the loading conditions of the system. The second part of the proposed characteristics is the exponential function of input voltage magnitude. An exponential function is chosen to fulfill the following conditions:

a) The magnitude of V depends on fault location with respect to relaying point. This magnitude can be zero for close-in bolted fault. Thus, exponential function is chosen to avoid the zero value of pickup current following zero value of input voltage.

b) In VR-OCR, the pickup current reduces with drop in input voltage. Thus, the proportional of exponential is considered with the exponential superscript being $(V - 1)$.

The proposed adaptive setting responds to faults in such system where fault current is lesser than the rated load current and fixed setting of the relay is inappropriate.

V. Simulation Results

Using MATLAB/Simulink [30], simulations are carried out and results have been obtained for different loading conditions at bus M and various fault resistances (R_F) for the system shown in Fig. 2. The PV plant configuration and system data are given in Appendix A. At sampling frequency of 1200 Hz, voltage and current phasors are computed using a full-cycle discrete Fourier transform.

A. Performance of proposed method for various fault resistance

For 50% loading at bus M, phase-A-to-ground fault with 0 Ω, 10 Ω, 50 Ω and 100 Ω fault resistances are simulated at F individually. For such cases, relay at bus R sense the fault and calculate the voltage and current magnitudes. Results are shown in Fig. 4. It is observed that with proposed setting, the relay is able to identify the fault correctly for various fault resistances, whereas fails for faults greater than 10 Ω with existing setting. It clearly shows that the performance of relay is improved by implementing proposed adaptive VR-OCR characteristics.

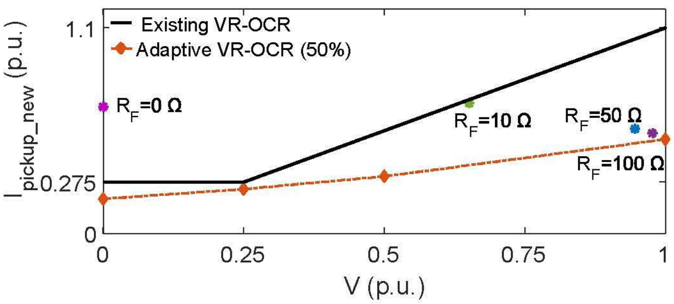

Fig. 4: Existing and Proposed adaptive VR-OCR characteristics for various fault resistances.

B. Performance of proposed method for different loading conditions

Phase-A-to-ground fault with 10 Ω fault resistance is created at F for 0%, 50% and 100% loading at bus M. For such cases, relay at bus R sense the fault and calculate the voltage and current magnitudes. Results are shown in Fig. 5. It is clear that existing method fails for 50% and 100% loading conditions because increase in loading reduces the current seen by the relay and maloperates the relay. On the contrary, the proposed setting updates the pickup characteristics with loading conditions and detects the fault correctly. It indicates that the adaptive pickup setting improves the performance of relay in case of high loading situation.

VI. Hardware-in-loop Validation

The proposed system is validated by means of two OPAL-RT simulators OP4510 [31] and IEC 61850 communication protocol [32]. The overall signal flow for hardware-in-loop (HIL) simulation is shown in Fig. 6. In simulator-1, the power system model, shown in Fig. 2, is simulated. In simulator-2, proposed adaptive relaying algorithm is built. The simulated voltage and current data are transferred as sample values (SV) from simulator-1 to simulator-2. The trip signal is sent back

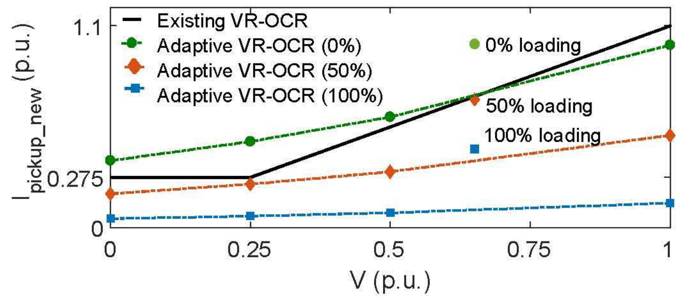

Fig. 5: Existing and Proposed adaptive VR-OCR characteristics for different loading conditions at bus M.

to the simulator-1 as generic object oriented substation event (GOOSE) message. The data and trip signal are exchange between the simulators through communication Protocol.

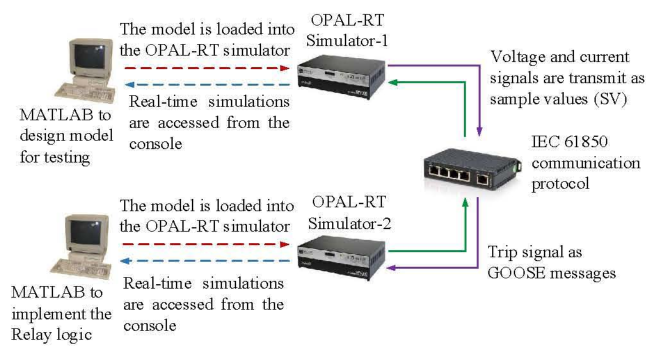

Fig. 6: Signal flow in hardware-in-loop simulation.

A three-bus distribution system (Fig. 2) with same loading conditions in Appendix A is simulated in simulator-1 and adaptive VR-OCR setting is built-in simulator-2. Phase-A-to-ground fault with 10 Ω fault resistance is created at 1.0 s in the middle of line segment RN with 50% loading at bus M. Fault current and fault voltage signals are sent to simulator-2. A trip signal is received at 1.048 s. It opens the circuit breaker 1.057 s and isolates the faulted line segment. The time difference between the fault inception and opening the circuit breaker is 57 ms, where full-cycle discrete Fourier transform took 16 ms for a 60 Hz system and communication latency is 32 ms. Fig. 7 shows the phase-A fault current simulated by simulator-1 and trip signal generated by simulator-2. Hardware-in-loop result validates the proposed method in real-time testing.

VII. Conclusion

In a distribution system, the loading conditions vary throughout a day. The performance of VR-OCR for protection of such PV connected distribution system is analyzed in this work. It is found that the variation of prefault loading condition influences the operation of VR-OCR significantly. An adaptive setting of VR-OCR is proposed in this work to protect the PV plant integrated distance system with changing loading conditions. The method updates its setting at each cycle in accordance with the prefault current seen by the relay and input voltage ranging from 0 p.u. to 1.0 p.u.. The performance

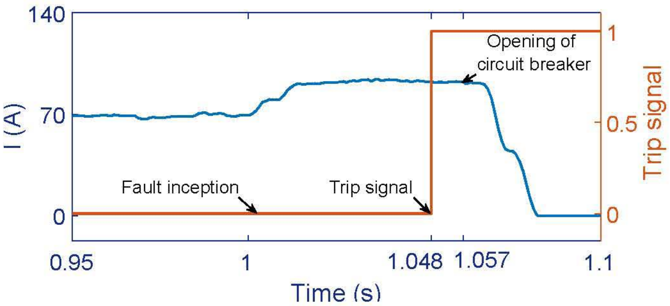

Fig. 7: Phase-A fault current and trip signal generated by the proposed setting.

of proposed relay is tested for different loading conditions and various fault resistances in the system. The method also validated in real-time using two OPAL-RT simulators and IEC 61850 protocol. Result confirms the applicability of the proposed method in PV connected distribution systems.

Future work will leverage the method for coordination of voltage restraint overcurrent relays with inverse or definite time characteristics.

Appendix A

The data are for 4.16 kV, 60 Hz power system.

Specifications of PV plant:

PV module specification:

Peak power = 1 MW;
Open circuit voltage = 64.2 V;
Maximum operating voltage = 54.7 V;
Short circuit current = 5.96 A;
Maximum operating current = 5.58 A;
Number of parallel modules = 660.

PV booster specification:

switching frequency = 5 kHz.
booster inductance = 5 mH;
booster capacitance = 60 mF;
DC-link voltage (V_{dc}) = 500 V;

PV inverter specification:

PV inverter rating = 1 MVA;
switching frequency (f_s) = 1980 Hz.
filter resistance (R_f) = 0.2 mΩ;
filter inductance (L_f) = 0.025 mH;
filter capacitance (C_f) = 0.390 mF;

Transformer specification:

1 MVA, 260 V/4.16 kV, ygYg.

Other system parameters:

Grid impedances:

$Z_g^+ = Z_g^- = 125\angle 60^\circ\ \Omega; Z_g^0 = 160\angle 62^\circ\ \Omega.$

Line impedances:

$Z_L^+ = Z_L^- = 9.5\angle 34^\circ\ \Omega; Z_L^0 = 20.9\angle 55^\circ\ \Omega.$

where subscripts g and L refer to grid and line respectively. Superscripts '+', '-' and '0' refer to positive, negative and zero sequences respectively.

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