Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 2859 – 2864

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Grid Side Unbalanced Fault Detection using Soft Open Point in an Electrical Distribution Network

Avinash Aithal[a*] Gen Li[a] Jianzhong Wu[a]

[a] *School of Engineering, Cardiff University.Cardiff. UK*

Abstract

Soft open point (SOP) is a power electronic device that installed in place of normally open points in distribution networks. This paper investigates the performance of SOP under an unbalanced line to ground (L-G) fault in a medium voltage (MV) distribution network. A method to detect unbalanced grid side AC faults was developed using positive and negative sequence currents injected into the feeder by the SOP. Simulations were carried out on a network model developed in PSCAD/EMTDC. Local measurements at SOP grid connection point were used to define a fault index. Results show that the fault index, based on the values of positive and negative sequence currents, is able to effectively detect the presence of an unbalanced fault in a MV distribution network.

Keywords: *Power electronics; Soft Open Points; Faults; Symmetrical components.*

1. Introduction

Power electronic devices have been increasingly deployed in distribution networks due to their application in integration of distributed energy resources (DER). Other applications of power electronic devices such as electronic on load tap changer, solid state fault current limiters and Soft open points (SOP) are under investigation [1], [2]. This paper focuses on the use of SOP for unbalanced fault detection in medium voltage (MV) distribution networks.

SOP is a power electronic device installed in place of a normally open or normally closed point in a distribution network [2], [3]. An SOP implemented using back-to-back voltage source converters (VSCs) is considered for this study. Other configurations of the SOP are discussed in [4].

Existing literature describes the behavior and benefits of SOP during normal network operation. Applications of SOP for load balancing and voltage profile management have been investigated in[5], [6] However, the existing literature does not describe the performance of SOP during abnormal unbalanced

* Corresponding author. Tel.: +44 7438550203;
E-mail address: AithalAV@cardiff.ac.uk.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.631

network conditions. To fill this gap, this paper investigates the interactions between the distribution network and an SOP during a line to ground (L-G) grid side AC faults.

A mechanism to detect faults is important to achieve proper operation of an SOP. Conventionally, separate fault management devices are used to detect the presence of a fault and disconnect the device from the network during an AC fault [7]. The VSC is reconnected to the grid only after the fault is isolated. In conventional operation scheme, an SOP has no role during abnormal condition of the network. the performance of an SOP under an unbalanced fault was investigated in this paper. Furthermore, a method was developed to detect a fault using the currents injected by the SOP during a fault. A fault index (*FI*) was defined to quantify the proportion of positive and negative sequence currents at the grid connection point of the SOP. The presence of a fault in the network can be determined by establishing a threshold of the *FI* value. This method is easy to implement since it only requires the local measurements at the grid connection point of SOP as inputs.

2. Principle of Analysis

2.1. Analysis of network using symmetrical components

Fortesque proposed the theory of symmetrical components in 1923 to study unbalanced networks [8]. During a fault, the unbalanced network can be resolved into three sets of balanced 3-phase vector groups (Positive, Negative and Zero sequence) called symmetrical components. During un-faulty operation, no negative and zero sequence components exist in the network. Eq. (1)-(3) show the measured phase voltages (V_a, V_b, V_c) expressed as a function of the symmetrical components. Similar equations can be written for the currents (I_a, I_b, I_c). Using these equations, the measured phase voltages and line currents are resolved into the positive, negative and zero sequence vectors. In the context of this research, the resolved vectors were used to compute the fault index for each phase.

$$V_a = V^p + V^n + V^z \tag{1}$$

$$V_b = a^2V^p + aV^n + V^z \tag{2}$$

$$V_c = aV^p + a^2V^n + V^z \tag{3}$$

The complex operator $a = e^{-\frac{3\pi j}{2}}$; subscript a, b, c indicates phase values and the superscripts ‘p’, ‘n’, ‘z’ represent positive, negative and zero sequence components respectively.

2.2. Definition of fault index

Fault index (*FI*), defined in Eq. 4, is the ratio of the difference between the root mean square (RMS) values of positive and negative sequence currents to the sum of positive and negative sequence currents for each phase. Similar function has been used for fault detection by Saeed Lotfi-fard et.al [9] to eliminate faulty operation of overcurrent protection devices due to transient currents in a network.

$$FI_x = \frac{(I^p_{x\,RMS} - I^n_{x\,RMS})}{(I^p_{x\,RMS} + I^n_{x\,RMS})} \tag{4}$$

x corresponds to phases a, b, c.

During an AC fault, an SOP behaves as a current source. The maximum current the SOP supplies is limited by the physical current limit (I_{max}) of the Insulated Gate Bipolar Transistors (IGBT). The maximum current injected by the SOP may saturate before the pick-up value of the overcurrent protection device in the network. Thus, conventional overcurrent based protection on the line may not be sufficient to detect the fault current. An SOP can produce positive and negative sequence currents using a classical '*dq*' controller. Details of the controller are explained in Section 3.

During a fault between the grid and the SOP, positive, negative and zero sequence currents are injected from both the grid and the SOP grid connection point. Thus, the current flowing into the fault is a sum of the current infeed from the grid and the current injected from the SOP. Zero sequence components exist in the network only if there is a grounding path available for the current to flow. Negative sequence components are present in the network during an imbalance. However, during an unbalanced fault the negative sequence current is present in a large proportion as compared to load imbalance. Thus, measuring the positive and negative sequence currents injected by the SOP is sufficient to detect the presence of an unbalanced fault in an AC network.

The power quality criterion is based on the voltage unbalance factor (*VUF*). *VUF* is the ratio of negative to positive sequence voltages. Engineering Recommendation P29 [10] states that the VUF does not go above 1.3%. To clearly distinguish between voltage imbalance and a fault, it is assumed that a value of $VUF \geq 0.1$ indicates a fault in the network. Considering a network with equal positive and negative sequence impedances, the ration of ratio of negative to positive sequence currents is equal to VUF. Applying this inequality in Eq. 4, the threshold value of $FI \geq 0.8$ was calculated for a healthy network. A value below 0.8 indicates a fault in the network.

3. Modelling of the test network and SOP

A generic radial distribution feeder, shown in Fig. 1, was used as a test network in this study. The network model was developed in PSCAD/ EMTDC package.

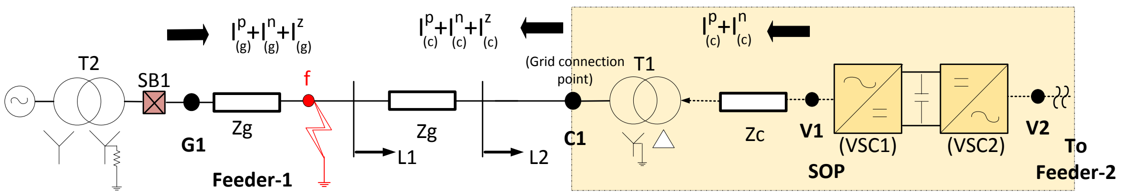

Fig. 1 Generic 11kV distribution network (Test network)

In Fig. 1, G1 is the grid infeed point. T2 is a star-star transformer grounded through a resistor on the feeder side. SB1 is the substation circuit breaker. Z_g represents the line impedance. Each section has a positive, negative and zero sequence impedance of 0.164 Ω, 0.164 Ω and 0.542 Ω respectively. For simplicity, the positive and negative sequence impedances are assumed to be equal. L1 and L2 are uniform lumped loads. C1 is the grid connection point of the SOP. A delta-star isolation transformer (T1) connects the converter terminal (V1) to the grid connection point on Feeder-1. Similarly, the other converter terminal (V2) is connected to Feeder-2 through an isolation transformer (not shown in the figure). Feeder-2 has been modelled identically to Feeder -1 with identical devices and line characteristics.

A back-to-back VSC based SOP is modelled with decoupled AC and DC sides as shown in Fig. 2(a). The AC side is modelled as a voltage source whereas the DC side is modelled as a current source parallel to a capacitor, as illustrated.

The VSC allows separate control of active power (*P)* and reactive power (*Q*) by controlling variables in the synchronous reference frame (*dq0* frame). Three-phase network variables are converted to the synchronous frame using Parks transformation. The transformed quantities are synchronised to the grid using angular frequency ω, obtained using phase locked loop [11]. The control of VSC is achieved through the classical two-level cascaded control system, which includes an outer and an inner control loop for individual VSC as shown in Fig. 2(b). The outer loop regulates the active power (or DC voltage (V_{dc})) and reactive power using PI controllers. The inner loop is used to regulate the reference values of the direct ($i_{d\ Ref}$) and quadrature current ($i_{q\ Ref}$) received from the outer loop. The PI controllers of the inner loop produce reference voltages $V_{d\ Ref}$ and $V_{q\ Ref}$. The reference voltages are used to generate the desired converter terminal voltage through pulse width modulation (PWM). A current limiter is defined by $(I_d)^2 + (I_q)^2 \le (I_{max})^2$. It ensures that the currents through the SOP terminals are within the physical limits of the IGBT. For this study, it is assumed that I_{max} is equal to 1.5 times the rated current.

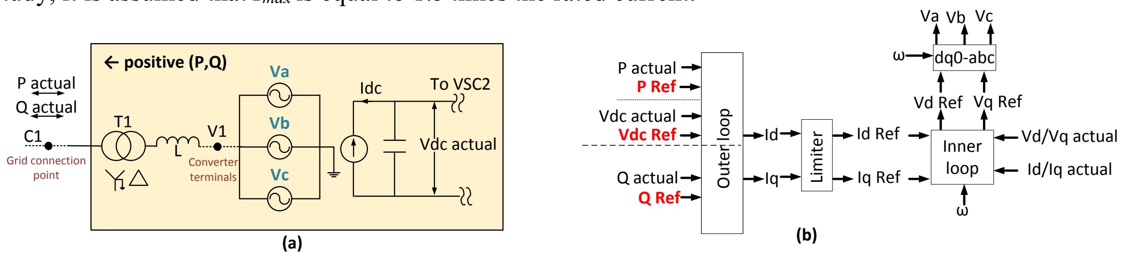

Fig. 2(a) Equivalent model of SOP ; (b) Classical two-level cascaded control system of SOP.

For each VSC, the control modes of the SOP are switchable between the *P*-*Q* and V_{dc}-*Q* modes. A sustained DC voltage ensures balanced power flow between the terminals of the SOP. Therefore, either VSC1 or VSC2 must invariably control V_{dc} for proper operation of SOP. The user defines reference values of the real power ($P_{1\ Ref}$ or $P_{2\ Ref}$), reactive power ($Q_{1\ Ref}$ and $Q_{2\ Ref}$) at terminals of VSC1 and VSC2 and DC voltage ($V_{dc\ Ref}$) as per network requirements.

4. Case studies and simulation results

The dynamic response of the SOP was investigated for an unbalanced fault on phase A, at the location ‘f’ on Feeder-1. This study focuses only on solid L-G faults. A temporary fault occurs at simulation time *t*=1s, for a duration of 0.6 seconds. The duration of the fault is assumed to be less than the time needed for SB1 to isolate the fault. The voltages, currents and powers at the grid connection point (C1) are analyzed under two main cases.

Case 1: For different control schemes of VSC1 i.e. in *P*-*Q* mode and V_{dc}-*Q* mode. The simulation results are analyzed for fixed set points of SOP. The following set points are used for this case assuming power flow from Feeder-2 to Feeder 1 is positive.

- VSC1 is in *P*-*Q* control and VSC2 is in V_{dc}-*Q* control: The set points of VSC1 are ($P_{1\,Ref} = +1\,MW$,$Q_{1\,Ref} = +0.5\,MVAr$) and set points of VSC2 are ($V_{dc\,Ref} = 35\,kV$,$Q_{2\,Ref} = -0.5\,MVAr$).
- VSC1 is in V_{dc}-*Q* control and VSC2 is in *P*-*Q* control: The set points of VSC1 are ($V_{dc\,Ref} = 35\,kV$,$Q_{1\,Ref} = +0.5\,MVAr$) and set points of VSC2 are ($P_{2\,Ref} = -1\,MW$,$Q_{2\,Ref} = -0.5\,MVAr$).

Case 2: For different $P_{1\ Ref}$ set points of VSC1, when VSC1 is in *P*-*Q* mode. $P_{1\,Ref} = 0\,MW$ and $P_{1\,Ref} = 2\,MW$, while other set points are the same as Case 1.

4.1. Case 1

The magnitude of positive, negative and zero sequence currents at the fault point ‘f’ are equal during a fault. This is consistent with the analytical calculation of an L-G fault on a network without SOP. Therefore, the contribution of negative and zero sequence currents from the grid is reduced by the introduction of SOP at the end of the feeder. The contribution from phase A of the SOP is shown in Fig. 3(a) and 3(b). The contribution from the SOP remains mostly unchanged for both modes of operation. Following a fault, the real and reactive powers flowing through the terminals of SOP are equal to the respective P_{Ref} and Q_{Ref} set points as shown in Fig. 4(a) and 4(b). A fluctuation of power flow measured at C1 is observed during the fault. The fluctuation is introduced as a result of a 2ω component in the currents, due to the unbalance in the network. For both control modes, the *FI* drops below the threshold value within 1 cycle (0.02s) of the fault as shown in Fig. 5(a) and 5(b). Following the drop of *FI* below the threshold value, the IGBTs can be blocked immediately. Conventional method using relay and isolator could take up to 30 cycles to detect and isolate the SOP. This method is considerably faster.

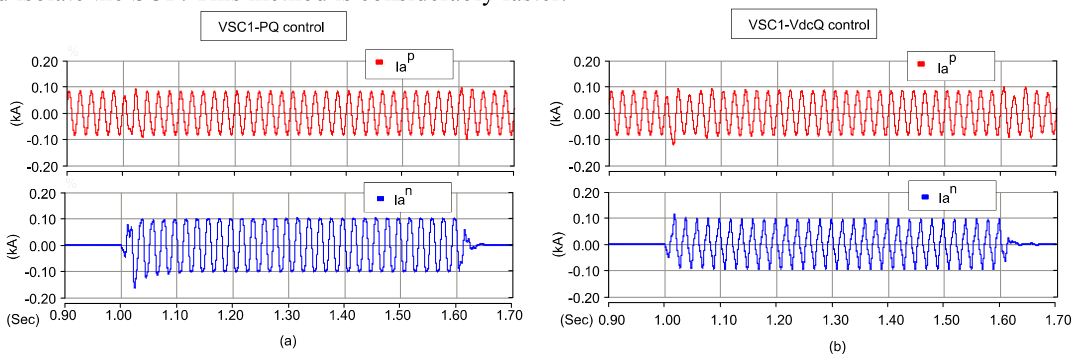

Fig. 3 Positive and negative sequence currents at C1 for VSC1 under (a) *P-Q* control; (b)V_{dc}-*Q* Control

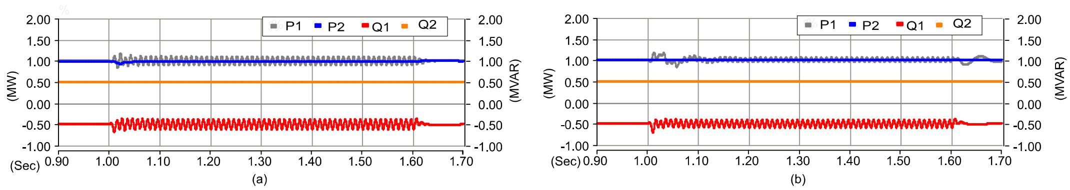

Fig. 4 Real and reactive power exchange at SOP termainals (a) *P-Q* control; (b)V_{dc}-*Q* Control

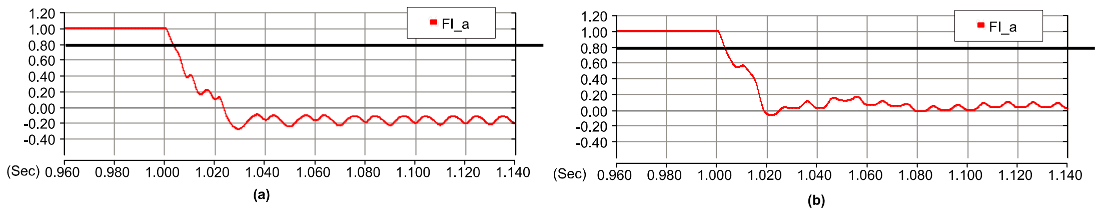

Fig. 5 Fault Index at C1 for VSC1 under (a) *P-Q* control; (b)V_{dc}-*Q* Control

4.2. Case 2

VSC1 does not produce zero sequence current since it is connected to the delta side of the isolation transformer. However, the fault current through 'f' has a zero sequence component since the grid transformer and the SOP isolation transformer are star grounded on the feeder side. When the SOP operates below the physical limits, the positive sequence currents depend upon the SOP operating set points. Whereas, the negative sequence currents depend on the network imbalance. For lower values of $P_{1\ Ref}$ set points, the *FI* could be negative. Fig. 6 (a) and (b) show the dependence of *FI* on the SOP set points. The positive sequence current contribution from the SOP for $P_{1\,Ref} = 0\,MW$ is considerably lower than the contribution for $P_{1\,Ref} = 2\,MW$. The negative sequence current remains the same for different set points.

However, the detection of a fault is unaffected for both set points, since the *FI* drops significantly below the threshold value.

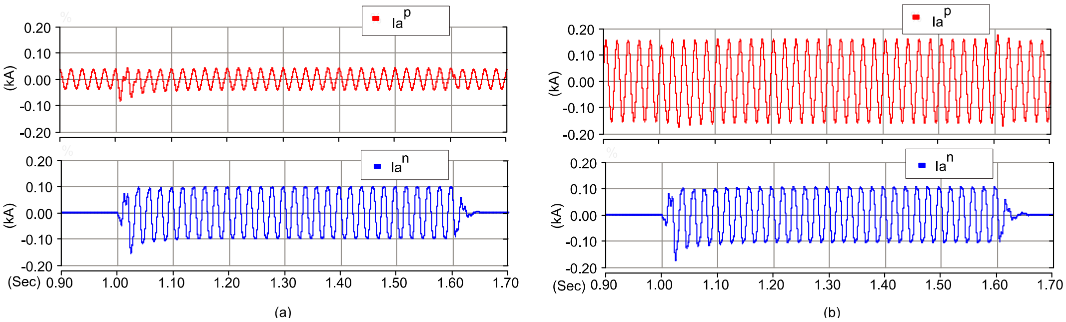

Fig. 6 Positve and negative sequence currents at C1 for (a) $P_{1\ Ref}$=0 MW; (b) $P_{1\ Ref}$=2 MW

5. Conclusion and future work.

This paper suggested an alternative use of SOP in an electrical distribution network. The efficacy of using the SOP for fault detection, without the use of additional protection equipment was investigated. The *FI*, defined using positive and negative sequence components of the current injected by the SOP is effective for fault detection in a network. This method is independent of the SOP control modes and require only local measurements available at the grid connection points. For the future work, the dependency of this method on network impedances and SOP set points will be investigated. Values of *FI* for each phase will further be utilized to develop the capability of the SOP to identify different types of faults.

Acknowledgements

This work was supported in part by the UK/India HEAPD project and Angle-DC project.

References

[1] T. Green and N. Jenkins, "HubNet Position Paper Series Issues for Distribution System Operation at 2030," 2014.

[2] R. Silversildes, T. Green, and T. Luth, "HubNet Position Paper Series - Power Electronics in Distribution System Management - Version 0.6," 2014.

[3] J. M. Bloemink and T. C. Green, "Benefits of Distribution-Level Power Electronics for Supporting Distributed Generation Growth," *IEEE Trans. Power Deliv.*, vol. 28, no. 2, pp. 911–919, Apr. 2013.

[4] J. M. Bloemink and T. C. Green, "Increasing photovoltaic penetration with local energy storage and soft normally-open points," in *2011 IEEE Power and Energy Society General Meeting*, 2011, pp. 1–8.

[5] W. Cao, J. Wu, N. Jenkins, C. Wang, and T. Green, "Operating principle of Soft Open Points for electrical distribution network operation," *Appl. Energy*, vol. 164, pp. 245–257, 2016.

[6] W. Cao, J. Wu, N. Jenkins, C. Wang, and T. Green, "Benefits analysis of Soft Open Points for electrical distribution network operation," *Appl. Energy*, vol. 165, pp. 36–47, 2016.

[7] J. Candelaria and J. D. Park, "VSC-HVDC system protection: A review of current methods," *2011 IEEE/PES Power Syst. Conf. Expo. PSCE 2011*, pp. 1–7, 2011.

[8] B. Y. C. Fortescue, "The Measurement of Power in Polyphase Circuits *," *J. Am. Inst. Electr. Eng.*, vol. 42, no. 3, pp. 205–218., 1923.

[9] S. Lotfi-fard, J. Faiz, and M. R. Iravani, "Improved overcurrent protection using symmetrical components," *IEEE Trans. Power Deliv.*, vol. 22, no. 2, pp. 843–850, 2007.

[10] The Electricity Council, "Planning Limits for Voltage Unbalance in the United Kingdom," *Engineering Recommendation P29*. p. 8, 1990.

[11] A. Yazdani and R. Iravani, "Grid Imposed Frequency VSC system: Control in dq-Frame," in *Voltage-sourced converters in power systems: modeling, control, and applications*, John Weley & Sons, 2010, pp. 204–245.