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Operating principle of Soft Open Points for electrical distribution network operation

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HIGHLIGHTS

- Two control modes were developed for a B2B VSCs based SOP.
- The SOP operating principle was investigated under various network conditions.
- The performance of the SOP using two control modes was analyzed.

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ABSTRACT

Soft Open Points (SOPs) are power electronic devices installed in place of normally-open points in electrical power distribution networks. They are able to provide active power flow control, reactive power compensation and voltage regulation under normal network operating conditions, as well as fast fault isolation and supply restoration under abnormal conditions. Two control modes were developed for the operation of an SOP, using back-to-back voltage-source converters (VSCs). A power flow control mode with current control provides independent control of real and reactive power. A supply restoration mode with a voltage controller enables power supply to isolated loads due to network faults. The operating principle of the back-to-back VSCs based SOP was investigated under both normal and abnormal network operating conditions. Studies on a two-feeder medium-voltage distribution network showed the performance of the SOP under different network-operating conditions: normal, during a fault and post-fault supply restoration. During the change of network operating conditions, a mode switch method based on the phase locked loop controller was used to achieve the transitions between the two control modes. Hard transitions by a direct mode switching were noticed unfavourable, but seamless transitions were obtained by deploying a soft cold load pickup and voltage synchronization process.

1. Introduction

The widespread use of distributed energy resources, e.g., distributed generations (DG), energy storage and controllable loads, is anticipated in many countries but this can lead to operation problems including excessive fault level as well as violations of thermal and voltage limits [1,2]. In the UK, with the liberalization of the electricity market and the drive to reduce the number of long term interruptions of electricity supply, reliable and high quality power supply is becoming more vital than ever [3]. These drivers inevitably lead to new challenges in the operation of electrical power distribution networks.

Medium voltage (MV) distribution networks are usually operated in a radial configuration. Normally open points (NOPs) are built, connecting adjacent feeders, to provide alternative routes of electricity supply in case of planned or unplanned power outages [4]. Such network configuration allows the use of simple and inexpensive protection schemes as well as providing fast fault isolation to limit the propagation of network faults. However, there is a possibility of power flow being unbalanced between radial feeders due to different loading conditions, especially when a high penetration of intermittent DG and flexible demand presents in the distribution networks. This, in turn, leads to high power losses, increased peak currents and undesirable voltage excursions [5]. Moreover, even though there are many supply restoration

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approaches proposed to increase the reliability of existing radially operated networks, momentary interruptions still exist when a fault occurs [6].

Upgrading of distribution networks from their original radial structure to a normally closed loop configuration is attracting attentions [7,8]. A closed loop configuration is advantageous over a radial one because the load can be balanced between feeders resulting in better voltage profiles and improved reliability of power supply [7]. However, such loop configuration increases the risk of wide area failures because any single network fault can be propagated quickly over a wide area. Thus, more complicated and expensive protection schemes are required for an interconnected network configuration [8,9].

Power electronic devices installed in place of NOPs in a distribution network, namely 'Soft' Open Points (SOPs) have been proposed to combine the benefits of both radial and loop (mesh) operated network while avoiding the drawbacks of each [9]. Instead of simply opening/closing NOPs, SOPs control load transfer and regulate network voltage profile by flexibly controlling active/reactive power flow between adjacent feeders. Immediate fault isolation between interconnected feeders as well as fast supply restoration is also enabled using these devices. Therefore SOPs are able to improve distribution network operation as well as facilitate a large penetration of low carbon technologies into the distribution network.

Previous studies have advocated the benefits of SOPs for distribution network operation [9–11]. It has been shown in [9,10] that SOP is a desirable alternative to other voltage control strategies for supporting DG growth. The coordination of SOP with local energy storage to damp the transients caused by the large-capacity distributed photovoltaic installations was presented in [11]. These studies mainly focused on normal network-operating conditions.

The behavior of an SOP device – back-to-back VSCs – under abnormal network-operating conditions was analyzed in [12]. However, only the condition during a fault was considered. The control philosophy and performance of the SOP to support post-fault supply restoration have not been explored.

To fill this gap, two control modes were developed for the operation of a back-to-back VSCs based SOP. The operating principle of a back-to-back VSCs based SOP was investigated under both normal and abnormal network operating conditions. The performance of the SOP using the two control modes was analyzed under various network operating conditions. The importance of the soft cold load pickup and voltage synchronization process, which are essential for a smooth transition between control modes during the change of network operating conditions, was also investigated.

2. Back-to-back VSCs based Soft Open Point

Fig. 1a shows a two-feeder distribution network interconnected with a back-to-back VSCs based SOP. Two VSCs are located between the feeder endpoints and connected via a common dc link. The main circuit topology of the back-to-back VSCs is shown in Fig. 1b. It consists of a dc capacitor to provide an energy buffer and reduce dc side voltage ripple, two two-level three-phase insulated gate bipolar transistor (IGBT)-based VSC to generate voltage waveforms using pulse width modulation (PWM). Each VSC terminal is connected to a series filter whose inductance is represented by L. This inductance provides high-frequency harmonic attenuation, limits the rate of rise of short circuit current, and facilitates control of power flow. The line resistance and reactance between the filter and the feeder endpoint are neglected since the line between the filter and the feeder endpoint is short.

The back-to-back VSC is suitable for SOP operation due to the following characteristics:

(1) *Flexible active and reactive power control.* Both VSCs build their own voltage waveforms with desired amplitude and phase angle. This allows a full control of active power flowing through the dc link as well as independent reactive power supply or absorption at both interface terminals. Such controllability y enables SOP operation for normal network operating condition, which includes feeder load balancing, power loss reduction and voltage profile improvement.
(2) *Instantaneous and independent voltage control.* The voltage waveform built by the VSCs can be controlled dynamically within milliseconds thus enabling transient control, e.g. dynamic Volt/VAR control and power oscillation damping [13]. In addition, the VSC can build its own voltage without the need of an active source at the receiving end. Hence cold load pick up for supply restoration is achievable using such device.
(3) *Isolation of disturbances and faults.* Transient overvoltage and overcurrent of VSCs are able to be limited by control strategies [14], thus network disturbances or faults on one connected feeder can be isolated from the other side by VSCs.

Two control modes were defined to operate the back-to-back VSC based SOP under both normal and abnormal network operating conditions. The power flow control mode was used to (1) regulate both active and reactive power flow on the connected feeders under normal network-operating conditions and (2) isolate fault between the interconnected feeders when a fault occurs on one feeder. The supply restoration mode was used under post-fault supply restoration conditions to provide power supply for the isolated loads on one feeder through the other feeder.

- *Power flow control mode*

A dual closed-loop current-controlled strategy [15] was used to operate SOP for the control of the feeder power flow under normal network operating conditions. Such current-controlled strategy is advantageous because: (1) it provides de-coupled control of active and reactive power components and (2) it inherently limits the VSC current during network faults.

Fig. 2 presents the overall control structure. The outer power control loop, the inner current control loop and the phase locked loop (PLL) are the three main components. In the outer power control loop (Fig. 2a), one of the VSCs operates with the *P*–*Q* control scheme where the active and reactive power errors are transformed into the reference *d*–*q* current components, i_d^* and i_q^* through the PI controllers. Superscript asterisk denotes the reference values. The other VSC operates with the $V_{dc} - Q$ control scheme maintaining a constant dc side voltage for a stable and balanced active power flowing through the dc link. Dynamic limiters for i_d^* and i_q^* are inserted to enable overcurrent limiting during network faults and disturbances. In the inner current control loop (Fig. 2b), the reference VSC *d*–*q* voltage, V_{dm} and V_{qm} are determined through the PI controllers considering the *d*–*q* current errors. The cross-coupling inductance L is the inductance between the VSC terminal and the feeder endpoint, i.e., the filter inductance as shown in Fig. 1b. This L remains constant when the power flow control mode is used for the operation of SOP. The voltage feedforward and current feed-back compensations are used to get a good dynamic response [16]. After transforming V_{dm} and V_{qm} into the VSC terminal voltage by Park's transformation [17], the gate signals for the IGBTs are obtained through the PWM. The PLL is important for the connection of VSCs to the ac network in order to synchronize the output VSC voltage with the ac network voltage. A PLL control topology based on the *pq* theory is used [18], as shown in Fig. 2c. By using the sum of the products of the feedback