POWER QUALITY IMPROVEMENT USING ACTIVE CONDITIONING DEVICES IN A PREMIUM POWER PARK

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ABSTRACT

In this paper, an enhanced premium power quality (PPP) configuration based on a spot configuration is proposed to effectively mitigate power quality disturbances using combined active power and voltage conditioning devices. A new coordination algorithm is also proposed to achieve full-range coordination between the active conditioning devices, to ensure maximum reliability of the PPP configuration.

INTRODUCTION

Power quality disturbances such as voltage sag and harmonic distortion are considered as the most intricate issues among power engineers in the last three decades, which eventually may cause severe and costly interruptions in industrial plants [1]. Power suppliers tend to deliver energy to their customers through one-size-fits-all grades of power quality, which may not be acceptable and reliable for most of the sensitive industrial customers. Thus, the key solution to the economic improvement of overall quality, reliability, and availability (QRA) of the delivered power is to offer different levels of QRA based on the sensitivity degree and requirements of loads using a more reliable distribution configuration known as a premium power park (PPP) and advanced power electronic-based devices called as active conditioning devices. The objective of using active conditioning devices in a PPP is to efficiently mitigate power quality disturbances, such as harmonic distortion, voltage sag/swell and voltage variation within pre-specified limits [2].
Over the past two decades, various studies have focused on the concept of PPP, which led to the design and implementation of several practical PPP plans worldwide. In 1999, the world's first PPP was designed and implemented in an existing industrial park in Delaware, Ohio by Electric Power Research Institute to provide both technical and financial satisfaction for utility and customers [3]. The Hsinchu and Tainan Science-Based Industrial Parks are another practical example of implemented PPP, which was designed and developed between 1999 and 2002 by the Taiwan Power Company [4]. In 2005, a multi-terminal high voltage DC system-based PPP to was implemented to ensure uninterrupted power to sensitive loads using IGBT voltage source converters [5]. An extended custom power park was proposed to improve current and voltage profile of linear and nonlinear loads using dynamic voltage restorer (DVR), active power filter, solid state transfer switch (STS), and distributed generation (DG) [6]. Recently, an improved PPP configuration has been proposed to mitigate voltage sag/swell and voltage variations using STS, DVR, and D-STATCOM [7].
In this paper, a novel PPP configuration is proposed based on the spot network configuration using a combination of active power and voltage conditioning devices, solid state circuit breakers (SSCB), and a grid-connected DG in close electrical proximity. These devices are used to mitigate voltage sag/swell, voltage variation, harmonic distortion, and power interruption. The proposed PPP scheme is designed to provide three levels of QRA for standard, sensitive, and critical loads. A coordination algorithm is presented to ensure the maximum coordination between the utilized devices in the proposed PPP.

PROPOSED PPP CONFIGURATION

The proposed PPP configuration offers an improved and multi-level QRA to meet the load requirements. Figure 1 demonstrates a simplified single-line diagram of the proposed configuration, which incorporates a combination of SSCBs, Active Power Conditioner (APC), Active Voltage Conditioner (AVC), Circuit Breakers (CBs), and a grid-connected DG set. In the figure, the proposed PPP configuration is fed through three feeders with spot configuration, which is known as a more reliable network than the conventional one and is known to protect customer loads from long- and short-duration interruptions.

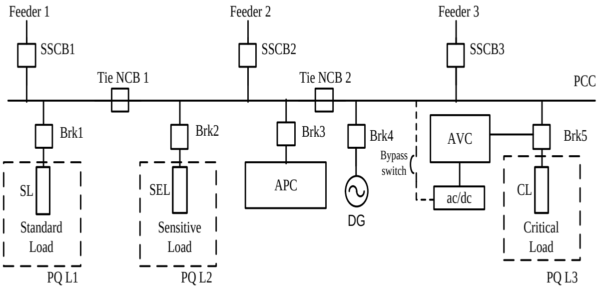

Figure 1. Single-line diagram of the proposed PPP

To show different levels of the required QRA, the loads in Figure 1 are divided into three categories, namely, standard load (L1), sensitive load (L2) and critical load (L3). Load L1 is a balanced induction motor load which is sensitive to voltage sag. Load L2 is an inverter-based harmonic polluting load which requires almost a voltage sag/swell and interruption-free power. Meanwhile, Load L3 is a critical load which cannot tolerate any disturbances.

In the proposed PPP configuration, all the incoming feeders are fed through SSCBs that are able to disconnect the faulty feeders for protecting customer loads from voltage sag with a depth of 40% or more and power interruptions. In addition, the APC can provide regulated voltage, correct power factor, and mitigate current harmonics for all loads at the Point of Common Coupling (PCC). When all SSCBs trip due to an upstream fault or deep voltage sag, the load side becomes isolated from the faulty feeders, and grid-connected DG provides the required power without interruption for sensitive and critical loads. Finally, the AVC is able to protect critical load voltage sags with a depth of 10% to 40%.

Proposed QRA Levels

The proposed PPP configuration offers three different QRA levels based on the requirements of customer loads, as follows:

1- Level QRA-L1: In this level, each SSCB disconnects its respective faulty feeder when voltage sag with a depth of 40% or more has occurred and all loads can be fed through other healthy feeders. In addition, APC can compensate voltage variation due to the inrush or motor starting currents, and provide harmonic free current for all loads at normal operation.

2- Level QRA-L2: This level can provide superior QRA level than the previous level by receiving the benefit of grid-connected DG as a continuous emergency power supply at the time of power interruption in addition to the advantages of SSCB and APC, which are essential for sensitive and critical loads.

3- Level QRA-L3: This level, which is above QRA-L2 level, can receive the benefits of AVC to protect critical load against voltage sags with a depth of 10% to 40% and voltage imbalances, in addition to the advantages of SSCB, APC, and DG.

COORDINATION ALGORITHM

To supervise different types of conditioning and controller devices and mitigate multiple disturbances simultaneously, a coordination algorithm is required. Figure 2 shows the proposed coordination algorithm to generate the on-off command for the PPP devices. Based on the proposed algorithm, under normal condition, the feeders continue feeding the customer loads through their respective SSCBs. However, when voltage sag with a depth of 40% or more occurs in an incoming feeder due to upstream faults, the respective SSCB disconnects the faulty feeder, and all loads are fed through the other healthy feeders. This open/close logic ensures that all loads receive the required power within the pre-determined sag level based on the baseline offered by the utility, except at the time of sustained interruption when all SSCBs trip due to the occurrence of voltage sag with a depth of 40% and more in all the incoming feeders. In this situation, the sensitive and critical loads can be fed through the DG, while the coordination centre sends an open command to the circuit breaker of standard load. Furthermore, when the sag level is between 10% and 40%, or the PCC voltage is unbalanced, the AVC provides additional voltage compensation for the critical loads. Finally, under normal operation conditions, when the PCC voltage is between 90% and 110% of the nominal voltage, the APC mitigates voltage variation and harmonic distortion for all loads connected to the PCC by injecting the required compensating current to the PCC.

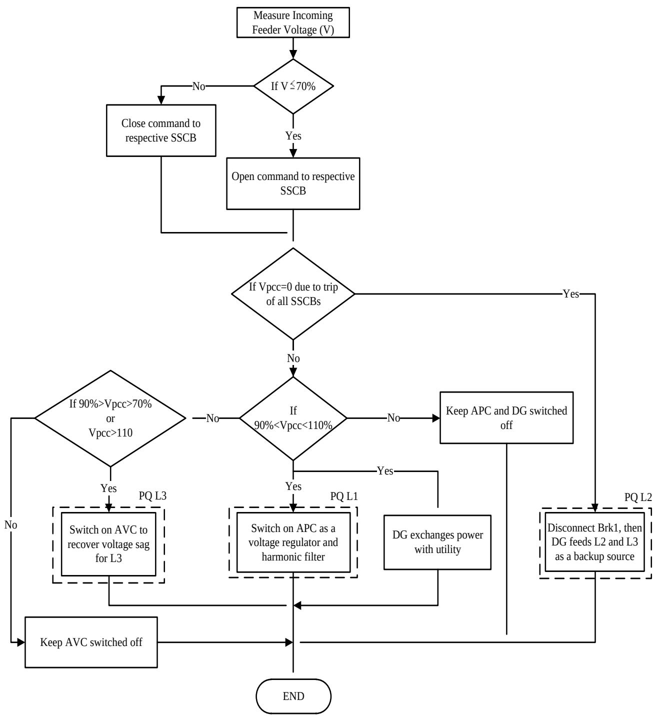

Figure 2. Proposed coordination algorithm

SIMULATION AND RESULTS

To test the performance and ability of the active conditioning devices in the proposed PPP configuration, when subjected to different types of power quality disturbances, a test system shown in Figure 1 is simulated using the Matlab/Simulink software. To evaluate the performance of the active conditioning devices, the following scenarios are considered in achieving QRA improvement:

1- Occurrence of voltage sags with a depth of 60% due to a symmetrical three-phase fault at feeder 3, to evaluate the SSCB performance in protecting the PCC voltages.

2- Occurrence of voltage sags with a depth of 30% with voltage imbalance due to an asymmetrical fault at feeder 1, to evaluate the AVC performance in protecting the L3 terminal voltages against voltage imbalances and voltage sags.

3- Occurrence of interruption due to the simultaneous three-phase to ground faults in all incoming feeders, to evaluate the DG performance as an emergency power supply for

sensitive and critical loads, L2 and L3.
4- Occurrence of voltage variation and harmonic distortion due to the motor starting effect of load, L1 and harmonic pollution of load, L2, to evaluate the APC performance in voltage regulation, power factor correction, and harmonic compensation.

Voltage Sag Mitigation at the PCC Using SSCBs

In this scenario, the feeder 3 voltage drops to 40% of nominal voltage due to an external symmetrical three-phase fault. Consequently, the SSCB3 trips the faulty feeder, and the required power is supplied by feeders 1 and 2 through SSCBs 1 and 2 to restore the PCC voltage to its pre-fault magnitude. Figure 3 shows the measured PCC voltage with and without the SSCB 3 operation.
The figures show that the SSCB3 controller can successfully identify the occurred voltage sag at 100 ms and recover the PCC voltage to its pre-fault level by disconnecting feeder 3 using its respective SSCB within one cycle, thus giving fast power restoration. After clearing the fault at 300 ms, the SSCB3 restores feeder 3 to continue supply power.

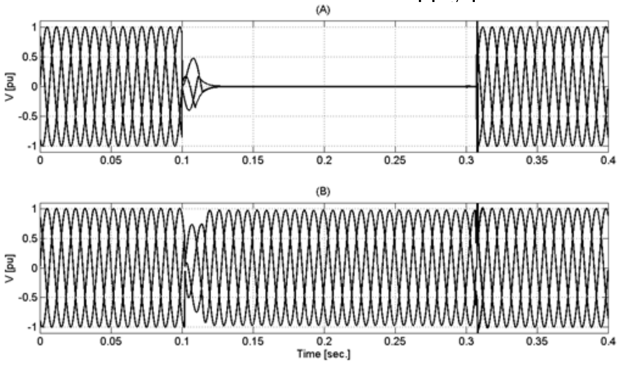

Figure 3. Measured PCC voltages (A) SSCB 3 is closed (B) SSCB 3 is opened

Voltage Sag and Voltage Imbalance Mitigation Using AVC

In this scenario, the PCC voltage drops to 70% of nominal voltage due to the occurrence of an external asymmetrical three-phase fault at feeder 1. In this situation, the SSCB which are not sensitive to voltage sag with a depth of less than 40%, cannot detect the occurred voltage sag and imbalance. Thus, the AVC detects this voltage sag and restores the voltage magnitude to its pre-fault level at the L3 terminal. Figure 4 shows the injected power by AVC and the measured voltage at the L3 terminal. From the figure, it is shown that the AVC can successfully balance and recover voltage up to 98% of its nominal voltage. The AVC is able to compensate voltage sag for an unlimited time interval, because it provides the required energy directly through the grid.

Voltage Interruption Mitigation at L2 and L3 Using DG

In this scenario, three simultaneous external three-phase to ground faults at all incoming feeders are created to generate a 60% voltage sag in each feeder. Based on the coordination algorithm, the SSCB controllers will identify the occurred voltage sag and each SSCB trips its respective feeder in a few milliseconds. Consequently, the PCC voltage drops to zero, and voltage interruption is said to occur. The coordination centre sends the command signal to open the circuit breaker, Brk1, and disconnect standard load, L1, from the PCC, and the DG continues to supply power to the sensitive and critical loads, L2 and L3, as a backup power supply. After clearing the external fault and returning the system to the normal condition by restoring the incoming feeders, DG keeps its power exchange mode with the network. Figure 5 shows the injected power by DG into the network, and the measured voltages at the load terminals for this scenario.

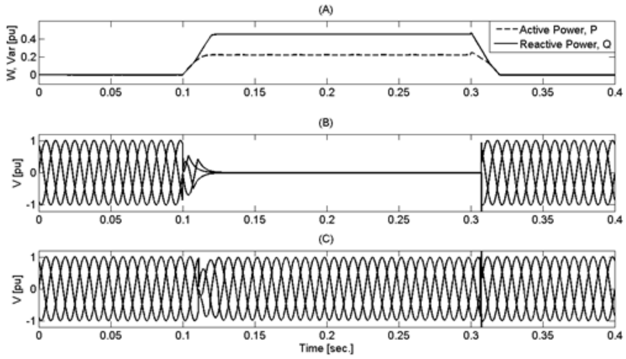

Figure 4. Injected power and measured voltages at L3 terminal (A) AVC injected active and reactive powers (B) Measured voltages at L3 without AVC (C) Measured voltages at L3 with AVC

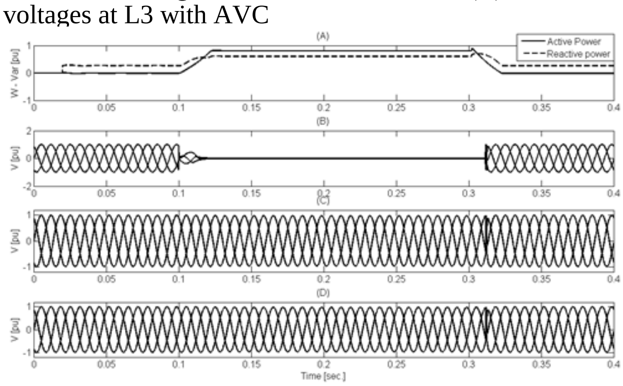

Figure 5. Injected power and measured voltages at the load terminals (A) DG injected active and reactive powers (B) L1 terminal voltage (C) L2 terminal voltage (D) L3 terminal voltage

Power Quality Improvement Using APC

To demonstrate the effectiveness of the APC for performing voltage regulation at the PCC, an inrush current is simulated by means of induction motor starting. This inrush current causes an 8.5% voltage drop in the PCC voltage. After identifying the voltage variation, the required current to compensate the PCC voltage is injected by APC. Figure 6 depicts the amount of injected active and reactive powers by the APC and the PCC voltage regulated by the APC. To investigate the performance of the APC in compensating harmonics, it is assumed that load L2 injects harmonic current into the network with 26.84% of current THD. The APC controller injects the required harmonic current and thereby reduces the voltage THD to 1.56%, which is well below its limit as given in the IEEE Std 519-1992. Figure 7 shows the measured voltage at the PCC before and after harmonic compensation by APC.

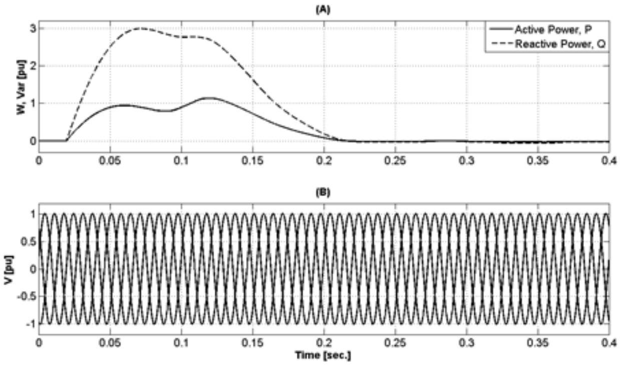

Figure 6. Performance of APC in voltage regulation (A) APC injected active and reactive powers at the PCC (B) Measured voltage at the PCC when APC is switched on

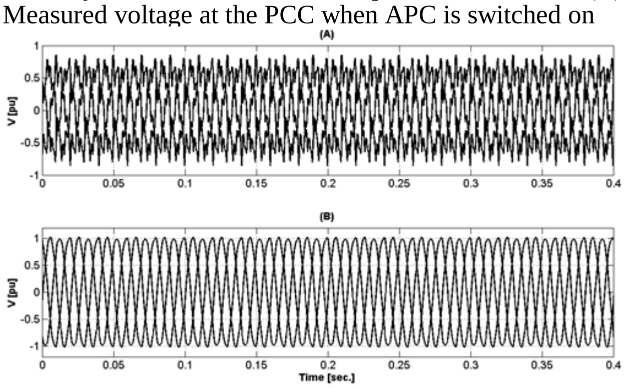

Figure 7. Measured voltage at the PCC (A) Without APC (B) With APC

Table 1 shows a comparison of the proposed PPP with the conventional PPPs [7] in enhancing power quality.

Table 1. Comparison between the functions of the proposed and conventional PPPs

Functions	Proposed PPP	Config. in [8]	Config. in [6]	Config. in [7]	Config. in [9]
More reliable incoming feeder configuration	√	×	×	×	√
Different QRA level	√	×	√	√	×
Unlimited voltage sag compensation	√	√	×	×	√
Unlimited voltage imbalance compensation	√	√	×	×	√
Voltage regulation	√	√	√	√	√
Harmonic mitigation	√	√	√	√	×
Uninterrupted/ unlimited backup power supply	√	Not completely	Not completely	×	×

CONCLUSION

The operation and control of active conditioning devices, namely, SSCB, APC and AVC in an enhanced PPP configuration is presented. In the proposed PPP configuration, the distributed customer loads are fed through three feeders with spot network structure, and each feeder is equipped with a SSCB to remove deep voltage sags and deliver more reliable power. In addition, the APC and AVC offer three improved levels of QRA for non-sensitive, sensitive, and critical loads. Four operating scenarios are simulated and a coordination algorithm is developed to illustrate the effectiveness of the active conditioning devices in mitigating power quality disturbances. Results prove that the active conditioning devices in the proposed PPP configuration are capable of mitigating power quality disturbances, including voltage sag, imbalance, harmonic, voltage variation, and interruption.

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