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An Interline Dynamic Voltage Restoring and Displacement Factor Controlling Device (IVDFC)

A. Elserougi, A. Massoud, *Senior Member, IEEE*, A. S. Abdel-Khalik, *Senior Member, IEEE*, S. Ahmed, *Senior Member, IEEE,* and A. Hossam-Eldin

***Abstract*—An Interline Dynamic Voltage Restorer (IDVR) is invariably employed in distribution systems to mitigate voltage sag/swell problems. An IDVR merely consists of several dynamic voltage restorers (DVRs) sharing a common DC-link connecting independent feeders to secure electric power to critical loads. While one of the DVRs compensates for the local voltage sag in its feeder, the other DVRs replenish the common DC-link voltage. For normal voltage levels, the DVRs should be bypassed. Instead of bypassing the DVRs in normal conditions, this paper proposes operating the DVRs, if needed, to improve the displacement factor (DF) of one of the involved feeders. DF improvement can be achieved via active and reactive power exchange (*PQ* sharing) between different feeders. To successfully apply this concept, several constraints are addressed throughout the paper. Simulation and experimental results elucidate and substantiate the proposed concept.**

***Index Terms*— Displacement factor Improvement, IDVR, IVDFC, and *PQ* sharing mode.**

NOMENCLATURE

rms	Root mean square
VC	Voltage control mode
PC	Power control mode
PCC	Point of common coupling
$v_{inj}(t)$, V_{inj}	Injected voltage (instantaneous, rms)
$v_s(t)$, V_S	Supply voltage (instantaneous, rms)
$v_L(t)$, V_L	Load voltage (instantaneous, rms)
V_{dc}	DC-link Voltage
v^*_{inj}	Converter (injected) voltage reference
β	Phase difference between $v_s(t)$ and $v_L(t)$
φ	Angle of load impedance
θ_{vs}	Angle of supply voltage
P_{ex}	Exchanged active power
ΔP	Required active power to replenish the DC-link
DF_L	Displacement factor at load
DF_d , DF_a	Desired, Accepted DF
V	Voltage magnitude (rms)
I	Current magnitude (rms)
P_s	Supplied active power
P_L	Load active power
*	Reference value
Subscript	
1	Sourcing feeder
2	Receiving feeder

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A. Elserougi, A. S. Abdel-Khalik, and Ahmed Hossam-Eldin are with the Department of Electrical Engineering, University of Alexandria, Alexandria 21544, Egypt (email:ahmed.abbas@spiretronic.com;ayman@spiretronic.com; a.hossamudn44@gmail.com).

A. M. Massoud is with the Department of Electrical Engineering, Qatar University, Doha, Qatar, and also with the Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt (e-mail: ahmed.massoud@qu.edu.qa).

S. Ahmed is with Texas A&M University at Qatar, Doha, Qatar (e-mail: shehab.ahmed@qatar.tamu.edu)

I. INTRODUCTION

DISTRIBUTION networks are mostly inductive at the fundamental frequency because of the nature of the dominant connected loads (e.g. induction motors). This in turn reduces the displacement factor (DF) and places an additional burden on the electrical supply. Low DF operation is not recommended due to several negative effects on the power system [1] including:

- Higher current for a given active power and a corresponding increase in total copper loss (i.e. system efficiency decrease).
- Lower utilization of power system components.
- Voltage regulation issues and rising power delivery costs.

Several practical techniques are commonly used to improve DF [1]. DF improvement employing capacitor banks with size and location optimization has been introduced in [2]. The optimal location and size of the capacitor bank to be placed in radial distribution feeders to improve their voltage profile and to reduce the total energy loss are presented in [3]. Different techniques are employed in [4] to minimize the power loss in distribution networks. In [5], the feeder reconfiguration concept in distribution systems is introduced to reduce system loss. In [6], a combined system for harmonic suppression and reactive power compensation is proposed not only to improve the DF but also the power factor.

A STATCOM [7]-[11] can be used as a viable alternative for DF improvement. Suitable adjustment of the phase and magnitude of the STATCOM output voltages enable effective control of active as well as reactive power exchanges between the STATCOM and the distribution system. Such a configuration allows the device to absorb or generate controllable active and reactive powers. A STATCOM has various features, including fast response, low-space requirement, and good stability margins. Recently, it is rapidly replacing the conventional naturally commutated reactive power controllers and static VAR compensators [12]. The reactive power supplied by the STATCOM for DF improvement is capacitive in nature. Intuitively, the higher the STATCOM's reactive power, the higher the DC-link voltage of the STATCOM (the higher the voltage requirements of the semiconductor devices).

The DVR is one of the most common and effective solutions for protecting critical loads against voltage sags [13], [14]. The DVR is a power electronic device used to inject three-phase voltages in series and in synchronism with the distribution feeder voltages in order to compensate for voltage sags. Moreover, it can be effectively used to enhance the fault ride through capability in wind applications [15]. Detection time is an important factor in the voltage restoration process. Fast detection algorithms and effective control schemes for a DVR are proposed in [16] and [17] respectively. Space vector modulation (SVM) is the recommended modulation scheme in a DVR due to its simple digital realization and improved DC-link utilization [18].

In distribution systems, load voltage restoration can be achieved by injecting active and/or reactive power into the distribution feeder. Active power capability of the DVR is governed by the capacity of the energy storage element and the employed compensation technique [19]. Several control techniques have been proposed for voltage sag compensation, such as pre-sag, in-phase, and minimal energy control approaches [20].

If the required power for voltage restoration is obtained from the neighboring feeder(s), the compensating device is technically called an inter-line dynamic voltage restorer (IDVR) [21]. The basic concept behind the IDVR is derived from the interline power flow controller (IPFC) proposed by Gyugyi in 1999 [22] to exchange power between parallel transmission lines. The two converters of the IPFC shown in Fig. 1 are used to control the transmitted power in each line (P_1 and P_2) and active power transfer between lines (P_{12}). With respect to the line current, the injected voltage has two components. The quadrature component provides reactive power compensation for the line, while the in-phase component absorbs or generates the required active power.

The main differences between an IPFC, IDVR, and the proposed system are summarized in Table I. In this table, the IPFC, which is used in transmission applications, is compared with an IDVR and IVDFC which are considered for distribution systems. It should be noted that the IPFC was the inspiration for proposing the IDVR for distribution networks. The IDVR can be used to mitigate voltage sag, or swell, at critical loads in distribution systems [21], [23]. It consists of several back-to-back voltage source converters with common DC-link connecting independent feeders as shown in Fig.2.

Each converter can be operated in either power control (PC) or voltage control (VC) modes. If one of the feeders is subjected to voltage sag, its converter will operate in VC mode and the required power for voltage restoration will be absorbed from the DC-link. In this state, the other converters connected to the healthy feeders should be switched to power control (PC) mode to replenish the DC-link voltage; a power-sharing scheme to determine the reference power of each healthy feeder is presented in [24].

The injected voltage in a healthy feeder during PC mode should have two components. The first component is in-phase with line current, which absorbs active power from the supply and provides it to the DC-link to support its voltage. The second component is in quadrature with the line current and is used to avoid load voltage magnitude perturbations after voltage injection as shown in Fig.3. In previous work [25], the injected voltage in a healthy feeder is emulated by using the virtual impedance.

During normal operating conditions (i.e. all feeders are healthy), the DVRs are typically bypassed via bypass switches, or they can be alternatively used for load sharing purposes as presented in [26]. Instead of bypassing the IDVR in normal operation, this paper proposes a new operational mode, namely *PQ* sharing mode, to improve the DF of one of the involved feeders by sharing active and reactive power among different system feeders through the buffering stage (the common DC-link). To apply this concept, several constraints are observed throughout the paper. The proposed interline dynamic voltage restoring and displacement factor controlling device (IVDFC) is supported using simulation and experimental results.

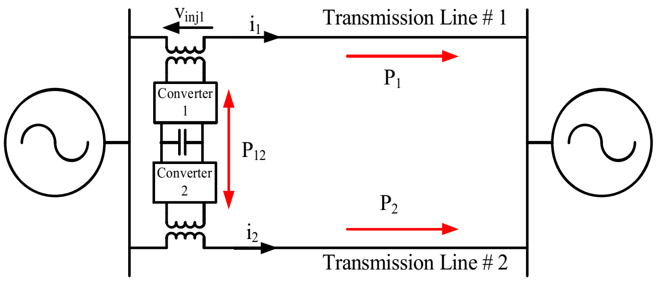

Fig. 1. Single line diagram of an IPFC in transmission system

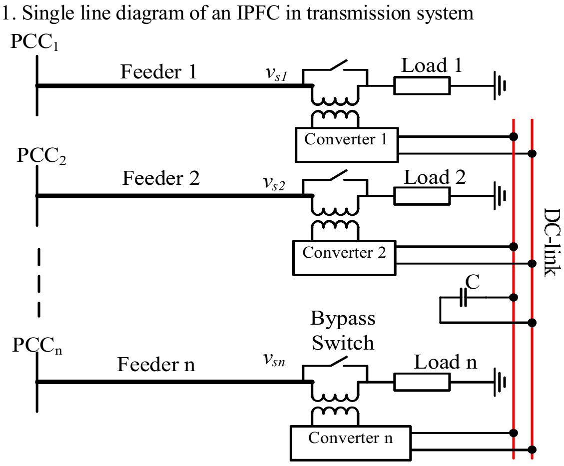

Fig. 2. Single line diagram of multi-line IDVR in the distribution system