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# Modeling Optimization Voltage Index Unified Power Flow Controller Equivalent Impedance

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## ABSTRACT

*This paper presents an active-reactive power control strategy for voltage source converters (VSCs) based on derivation of the direct and quadrature components of the VSC output current. The proposed method utilizes a multivariable proportional-integral controller and provides almost completely decoupled control capability of the active and reactive power with almost full disturbance rejection due to step changes in the power exchanged between the VSC and the grid. It also imposes fast transient response and zero steady-state error as compared to the conventional power control approaches. The applicability of the proposed power control strategy for providing the robust stability of the system against the uncertainties of the load parameters is also investigated. The superiority of the proposed control strategy over conventional approaches in the new condition of supplying the load is demonstrated. The theoretical aspects of the proposed multivariable-based power control strategy and the conventional approaches are reviewed and simulation results are presented in two separate sections. MATLAB/Simulink 2009a is used to simulate different scenarios of the simulation.*

**KEYWORDS:** *Unified power flow controller, equivalent impedance modeling, optimization, voltage index.*

## I. INTRODUCTION

Utilizing renewable energies such as distributed generation (DG) has become a great concern for utility grids to provide sufficient electrical energy to supply domestic and industrial requirements in a clean world. There are many types of these generations, including wind energy [1–5] and photovoltaic and fuel cells [6–9]. Many of these technologies adopt voltage source converters (VSCs) as an interface of distributed generators because of the nature of the output voltage. VSCs give us advantages including easy controllability and the capability to control circuit parameters like the voltage, current, or output power of the DG [10–15]. There are three types of control strategies adopted for the VSCs: 1) active-reactive power control (called PQ control), 2) active power-voltage control (PV control), and 3) voltage-frequency control (VF control). Many approaches utilized proportional-integral (PI)-based controllers to regulate the target variable at the desired level. PI controllers are universally known because of their simple implementation and tuning and for providing fast dynamics and zero steady-state error [16]. These controllers are always used for various applications of current regulation [17–23]. Regulating a variable in a rotating reference frame (RRF) is defined when time-varying variables (AC variables) are transferred to an orthogonal space like the dq0 domain, in which the frame rotates with an arbitrary angular speed of ω. This makes the variables appear as time-invariant quantities. Therefore, the designed controller can act like a DC/DC converter with zero steady-state error by providing an infinite gain at the operating point. In these methods, the controller should have the capability of decoupling the dq axis components of one variable such that the unwanted disturbances applied to one axis do not generate significant transients on the other one. This capability provides independent control of the desired variable, which could be the output current or the power of a converter. In [24], a multivariable

PI-based dq current control strategy based on a different design procedure than the conventional approaches [25] was proposed to reach the desired decoupling between the two d and q axis components of the line current. The presented method provides much less transient effect against incoming disturbances and zero steady-state error on tracking the reference values; moreover, it has a simple structure and is easy to implement. However, in the utility grids, due to changes in the demanded power imposed by the loads, what is important is that the distributed generators with power electronic interface could supply the requested power. This could be possible by applying the appropriate methods. The decoupling capability between the two d and q axis components of the current is also applicable for the active and reactive power exchanged between the VSC and grid. In [26], a classical droop control method was utilized to achieve the grid impedance. The virtual real and reactive power frame transformation was then used to result in decoupling power control capability. Wei and Kao [27] proposed a power control strategy based on placing a virtual inductance at the inverter output in a low-voltage microgrid. The impedance voltage droop and the local load effects were considered to prevent the coupling between the active and reactive output power, but one of the problems of the conventional droop control method is the assumption that the output impedance is mainly inductive. To avoid using extra output inductance, fast control loops were added to the droop method [28]. In [29], a control scheme was utilized that used the voltage and current variation at the point of common coupling due to small changes of the VSI power for estimating the grid impedance so that power flow control could be possible in all conditions of the grid including on-grid or autonomous mode.

In this paper, the application of a multivariable PI-controller in the power control strategy for VSC-based DG has been presented. In the proposed method, first the reference values of direct and quadrature components of the converter output current are determined directly from specified power references. Because these values are proportional to the active and reactive output power, respectively, a controller is then utilized to regulate the output power at the desired level. The capability of the designed controller has been shown from various points of view: 1) improvement of the transient response, 2) zero steady-state error in tracking the power reference values, 3) capability of minimizing the effect of step changing in output active or reactive power on one another for decoupling control capability of these powers, and 4) robust stability of the controller against uncertainties of load parameters. MATLAB/Simulink 2009a has been used to simulate the different scenarios of the simulation.

## II. RELATED WORK

For the purpose of this article, we shall define power quality problems as: ‘Any power problem that results in failure or disoperation of customer equipment, manifests itself as an economic burden to the user, or produces negative impacts onthe environment.’

When applied to the container crane industry, the power issues which degrade power quality include:

- Power Factor
- Harmonic Distortion
- Voltage Transients
- Voltage Sags or Dips
- Voltage Swells

The AC and DC variable speed drives utilized on board container cranes are significant contributors to total harmonic current and voltage distortion. Whereas SCR phase control creates the desirable average power factor, DC SCR drives operate at less than this. In addition, line notching occurs when SCR’s commutate, creating transient peak recovery voltages that can be 3 to 4 times the nominal line voltage depending upon the system impedance and the size of the drives. The frequency and severity of these power system disturbances varies with the speed of the drive. Harmonic current injection by AC and DC drives will be highest when the drives are operating at slow speeds. Power factor will be lowest when DC drives are operating at slow speeds or during initial acceleration and deceleration periods, increasing to its maximum value when the SCR’s are phased on to produce rated or base speed. Above base speed, the power factor essentially remains constant. Unfortunately, container cranes can spend considerable time at low speeds as the operator attempts to spot and land containers. Poor power factor places a greater kVA demand burden on the utility or engine-alternator power source. Low power factor loads can also affect the voltage stability which can ultimately result in detrimental effects on the

Life of sensitive electronic equipment or even intermittent malfunction. Voltage transients created by DC drive SCR line notching, AC drive voltage chopping, and high frequency harmonic voltages and currents are all significant sources of noise and disturbance to sensitive electronic equipment

It has been our experience that end users often do not associate power quality problems with Container cranes, either because they are totally unaware of such issues or there was no economic Consequence if power quality was not addressed. Before the advent of solid-state power supplies, Power factor was reasonable, and harmonic current injection was minimal. Not until the crane Population multiplied, power demands per crane increased, and static power conversion became the way of life, did power quality issues begin to emerge. Even as harmonic distortion and power Factor issues surfaced, no one was really prepared. Even today, crane builders and electrical drive System vendors avoid the issue during competitive bidding for new cranes. Rather than focus on Awareness and understanding of the potential issues, the power quality issue is intentionally or unintentionally ignored. Power quality problem solutions are available. Although the solutions are not free, in most cases, they do represent a good return on investment. However, if power quality is not specified, it most likely will not be delivered.

Power quality can be improved through:

- Power factor correction,
- Harmonic filtering,
- Special line notch filtering,
- Transient voltage surge suppression,
- Proper earthing systems.

In most cases, the person specifying and/or buying a container crane may not be fully aware of the potential power quality issues. If this article accomplishes nothing else, we would hope to provide that awareness.

In many cases, those involved with specification and procurement of container cranes may not be cognizant of such issues, do not pay the utility billings, or consider it someone else's concern. As a result, container crane specifications may not include definitive power quality criteria such as power factor correction and/or harmonic filtering. Also, many of those specifications which do require power quality equipment do not properly define the criteria. Early in the process of preparing the crane specification:

- Consult with the utility company to determine regulatory or contract requirements that must be satisfied, if any.
- Consult with the electrical drive suppliers and determine the power quality profiles that can be expected based on the drive sizes and technologies proposed for the specific project.
- Evaluate the economics of power quality correction not only on the present situation, but consider the impact of future utility deregulation and the future development plans for the terminal

## III. IMPLEMENTATION

### *3.1 System description and modeling:*

A single-line diagram of the three-phase test system adopted for evaluating the performance of the proposed method is shown in Figure 1. In this system, a distributed generation unit is connected to the grid through a VSC interface module, with a series line reactor as a filter to reduce the harmonics generated due to the VSC and finally a coupling transformer to reach the grid voltage level. The DC side voltage of the VSC considered is constant like a battery. The internal resistance and inductance of the filter are considered as Rt and Lt , respectively. The inductance of the coupling transformer is latent in the filter inductance. The numerical values of the test system elements are given in the Table.

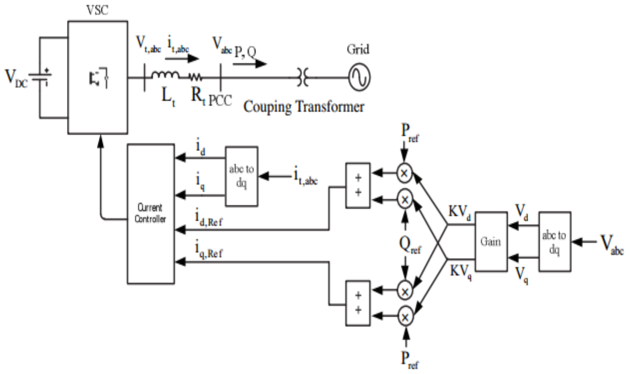

**Figure 1. One-line diagram of the test system.**

**Table.** Numerical values of the three-phase test system.

| Component | Value | Comment |
|---|---|---|
| $L_t$ | 4.5 mH | Inductance of the VSC filter |
| $R_t$ | 0.1Ω | Resistance of the VSC filter |
| $V_{dc}$ | 450 V | DC bus voltage |
| $V_s$ | 380 V | Grid nominal line to line voltage |
| $n_1$:$n_2$ | 4:1 | Transformer ratio |
| $S_{nominal,VSC}$ | 800 VAR | VSC rated power |
| $f_{sw}$ | 10 kHz | PWM carrier frequency |
| $f_s$ | 5 kHz | Sampling frequency |
| f | 50 Hz | System nominal frequency |

### *3.2 Mathematical model of the test system*

In this section, the mathematical model of the three-phase test system and its structure diagram is derived [30]. Based on Figure 1, which shows the structure of the test system, writing the KVL from the PCC bus to the converter terminal results in the dynamic equation of the VSC in the abc frame as below:

$$V_{t,abc} = R_t i_{t,abc} + L_t \frac{di_{t,abc}}{dt} + V_{abc}. \tag{1}$$

To design an applicable PI-based current controller in the rotating reference frame, Eq. (1), which is the dynamic representation of the system in the stationary rotating frame, should transform to the dq reference frame that rotates by the angular speed of ω. This transform could be done by the following expression:

$$F_{dq0} = K_S F_{abc}. \tag{2}$$

Eq. (2) transforms any abc quantities into the rotating frame, where Ks is defined as below:

$$K_S = \frac{2}{3}\begin{bmatrix} \cos\omega t & \cos(\omega t - 120) & \cos(\omega t + 120) \\ \sin\omega t & \sin(\omega t - 120) & \sin(\omega t + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}. \tag{3}$$

Therefore, the dynamic equation of the system in the RRF could result as in Eq. (4), in which the zero sequence has been neglected.

$$V_{t,dq} = R_t i_{t,dq} + L_t \frac{di_{t,dq}}{dt} + j\omega L_t i_{t,dq} + V_{dq} \tag{4}$$

The real and imaginary parts of Eq. (4) could be separated to achieve the dynamic equation of the system on the d and q direct axis in the RRF, such as in Eqs. (5) and (6). The block diagram of the test system is obtained in the dq frame by adopting Eqs. (5) and (6) and it is shown in Figure 2.

$$R_t i_{t,d} + L_t \frac{di_{t,d}}{dt} = V_{t,d} + \omega L_t i_{t,q} - V_d \tag{5}$$

$$R_t i_{t,q} + L_t \frac{di_{t,q}}{dt} = V_{t,q} - \omega L_t i_{t,d} - V_q \tag{6}$$

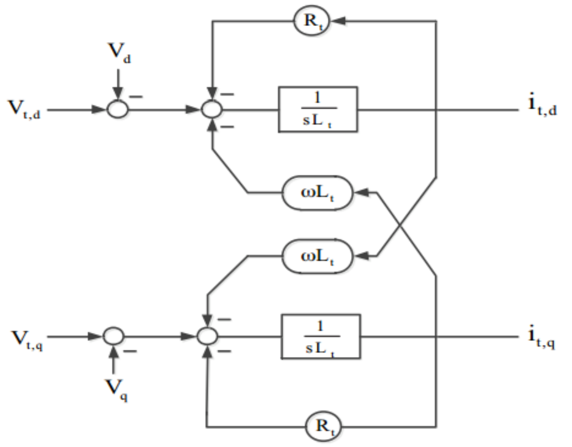

**Figure 2. Structure diagram of the test system model [3].**

## IV. EXPERIMENTAL WORK

The control results by different converter structures and control strategies are validated on a downscale dc–ac converter. As shown in Fig. 3, the circuit configurations and setup photo are both illustrated. A three-phase two-level converter with corresponding *LCL* filter is used to interconnect two dc voltage sources and a programmable three-phase ac voltage source. The detail parameters of the experimental setup are shown in Table III. It is noted that the converter is controlled to operate at the inverter mode, where the active power is flowing from the dc source to the ac source. By opening and closing a switch shown in Fig. 3(a), the converter can be shifted between the typical three-wire system and four-wire system with the zero-sequence current path. The amplitude of the phase A voltage in the programmable ac source is adjusted to 0.1 p.u. (22 Vrms) in order to establish an adverse unbalanced condition.

The control performance of the converter with the three-wire structure is shown in Fig. 4, where the given conditions and the two control strategies mentioned in Figs. 5 and 7 are applied, respectively. It can be seen that the experimental results agree well with the analysis and simulation results, where either the significant power oscillations or the overloaded current in the faulty phase are presented After enabling the zero current path and proposed controls, the performances of the given converter are shown again in Fig. 17, where the same conditions and two control strategies mentioned in Figs. 11 and 13 are applied, respectively. It can be seen that the experimental results also agree well with the simulation results, where the power oscillations are much more reduced or even totally cancelled; meanwhile, the current stress in the faulty phase is significantly relieved. These critical performances are hard to be achieved by a single three-wire converter structure using existing control strategies.

The capability to control the reactive power is also a critical performance for the converter under the unbalanced ac source, the proposed two control methods are also tested under the conditions to deliver the inductive/capacitive reactive power. As shown in Figs. 18 and 19, the *No P & No Q oscillation control* and *No negative-sequence current & No P oscillation control* are applied, respectively, to deliver the inductive and capacitive reactive power with phase A voltage dipping to 0.5 p.u. It can be seen that the advantages of the smaller/eliminated power oscillation and the relieved current loading in the faulty phase are still maintained. It is noted that the power delivering under the unbalanced AC source should give priority to the current limits of the power devices. This topic has been well discussed in the existing control methods based on the three-wire structure [30], and it is also an important consideration in the proposed control methods which utilize the zero-sequence components.

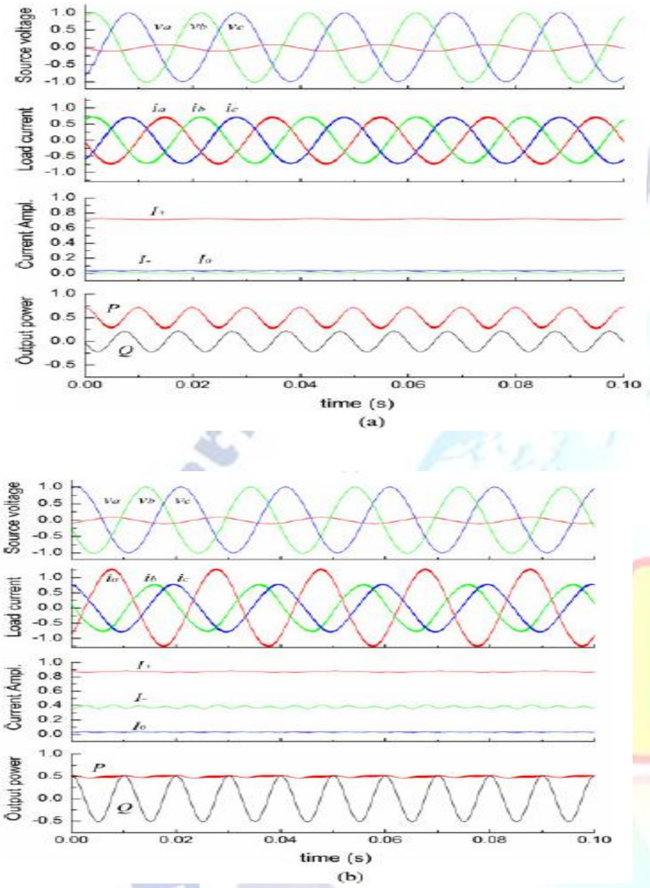

**Fig. 3. Experimental control performance of the converter in Fig. 3(a) with only three wires (units are nominalized by parameters in Table III, reference given: *Pref* = 0.5 p.u., *Qref* = 0 p.u., ac source condition: amplitude of the phase voltage *VA* = 0.1 p.u., *VB* =*VC* = 1 p.u.). (a) No negative-sequence current control (b) No P oscillation control.**

## V. CONCLUSION

In a typical three-phase three-wire converter structure, there are four current control freedoms, and it may be not enough to achieve satisfactory performances under the unbalanced ac source, because either significantly the oscillated power or the overloaded current will be presented. In the three phase converter structure with the zero sequence current path, there are six current control freedoms. The extra two control freedoms coming from the zero sequence current can be utilized to extend the controllability of the converter and improve the control performance under the unbalanced ac source. By the proposed fuzzy logic control strategies, it is possible to totally cancel the oscillation in both the active and the reactive power, or reduced the oscillation amplitude in the reactive power. Meanwhile, the current amplitude of the faulty phase is significantly relieved without further increasing the current amplitude in the normal phases. The advantage and features of the proposed controls can be still maintained under various conditions when delivering the reactive power. The analysis and proposed control methods are well agreed by experimental validations.

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