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A Battery Energy Storage System With Controlled Reduced-Rating Dynamic Voltage Restorer

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Abstract: **In this paper, different voltage injection schemes for dynamic voltage restorers (DVRs) are analyzed with particular focus on a new method used to minimize the rating of the voltage source converter (VSC) used in DVR. A new control technique is proposed to control the capacitor-supported DVR. The control of a DVR is demonstrated with a reduced-rating VSC. The reference load voltage is estimated using the unit vectors. The synchronous reference frame theory is used for the conversion of voltages from rotating vectors to the stationary frame. The compensation of the voltage sag, swell, and harmonics is demonstrated using a reduced-rating DVR. Power quality problems such as transients, sags, swells, and other distortions to the sinusoidal waveform of the supply voltage affect the performance of these equipment pieces. Technologies such as custom power devices are emerged to provide protection against power quality problems. Custom power devices are mainly of three categories such as series-connected compensators known as dynamic voltage restorers (DVRs), shunt-connected compensators such as distribution static compensators, and a combination of series and shunt-connected compensators known as unified power quality conditioner. The DVR can regulate the load voltage from the problems such as sag, swell, and harmonics in the supply voltages. Hence, it can protect the critical consumer loads from tripping and consequent losses. The custom power devices are developed and installed at consumer point to meet the power quality standards such as IEEE-519**

I. INTRODUCTION

Power quality problems in the present-day distribution systems are addressed in the literature due to the increased use of sensitive and critical equipment pieces such as communication network, process industries, and precise manufacturing processes. Power quality problems such as transients, sags, swells, and other distortions to the sinusoidal waveform of the supply voltage affect the performance of these equipment pieces. Technologies such as custom power devices are emerged to provide protection against power quality problems. Custom power devices are mainly of three categories such as series-connected compensators known as dynamic voltage restorers (DVRs), shunt-connected compensators such as distribution static compensators, and a combination of seriesand shunt-connected compensators known as unified power quality conditioner. The DVR can regulate the loadvoltage from the problems such as sag, swell, and harmonics in the supply voltages. Hence, it can protect the critical consumer loads from tripping and consequent losses.The custom power devices are developed and installed at consumer point to meet the power quality standards.

Voltage sags in an electrical grid are not always possible to avoid because of the finite clearing time of the faults that cause the voltage sags and the propagation of sags from the transmission and distribution systems to the low-voltage loads. Voltage sags are the common reasons for interruption in production plants and for end-user equipment malfunctions in general. In particular, tripping of equipment in a production line can cause production interruption and significant costs due to loss of production. One solution to this problem is to make the equipment itself more tolerant to sags, either by intelligent control or by storing “ride-through” energy in the equipment. An alternative solution, instead of modifying each component in a plant to be tolerant against voltage sags, is to install a plantwide uninterruptible power supply system for longer power interruptions or a DVR on the incoming supply to mitigate voltage sags for shorter periods . DVRs can eliminate most of the sags and minimize the risk of load tripping for very deep sags, but their main drawbacks are their standby losses, the equipment cost, and also the protection scheme required for downstream short circuits.

II. POWER QUALITY

The contemporary container crane industry, like many other industry segments, is often enamored by the bells and whistles, colorful diagnostic displays, high speed performance, and levels of automation that can be achieved. Although these features and their indirectly related computer based enhancements are key issues to an efficient terminal operation, we must not forget the foundation upon which we are building. Power quality is the mortar which bonds the foundation blocks.

Power quality also affects terminal operating economics, crane reliability, our environment, and initial investment in power distribution systems to support new crane installations. To quote the utility company newsletter which accompanied the last monthly issue of my home utility billing: ‘Using electricity wisely is a good environmental and business practice which saves you money, reduces emissions from generating plants, and conserves our natural resources.’ As we are all aware, container crane performance requirements continue to increase at an astounding rate.

Next generation container cranes, already in the bidding process, will require average power demands of 1500 to 2000 kW – almost double the total average demand three years ago. The rapid increase in power demand levels, an increase in container crane population, SCR converter crane drive retrofits and the large AC and DC drives needed to power and control these cranes will increase awareness of the power quality issue in the very near future.

III. POWER QUALITY PROBLEMS

For the purpose of this article, we shall define power quality problems as:

‘Any power problem that results in failure or mis operation of customer equipment, manifests itself as an economic burden to the user, or produces negative impacts on the 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.

The schematic of a DVR-connected system is shown in Fig. 1(a). The voltage *V*inj is inserted such that the load voltage *V*load is constant in magnitude and is undistorted, although the supply voltage *Vs*is not constant in magnitude or is distorted. Shows the phasor diagram of different

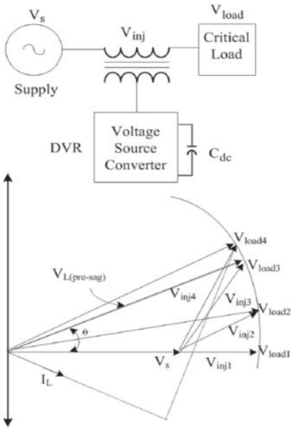


Fig. 1. (a) Basic circuit of DVR. (b) Phasor diagram of the DVR voltage injection schemes.

Voltage injection schemes of the DVR. $V_{L(\text{pre}-\text{sag})}$is a voltage across the critical load prior to the voltage sag condition. During the voltage sag, the voltage is reduced to *Vs*with a phase lag angle ofθ. Now, the DVR injects a voltage such that the load voltage magnitude is maintained at the pre-sag condition. According to the phase angle of the load voltage, the injection of voltages can be realized in four ways . V $_{\text{inj1}}$represents the voltage injected in-phase with the supply voltage. With the injection of V_{inj2}, the load voltage magnitude remains same but it leads *Vs*by a small angle. In *V*inj3, the load voltage retains the same phase as that of the pre-sag condition, which may be an optimum angle considering the energy source. $V_{\text{inj4}}$is the condition where the injected voltage is in quadrature with the current, and this case is suitable for a capacitor-supported DVR as this injection involves no active power. However, a minimum possible rating of the converter is achieved by V_{inj1}. The DVR is operated in this scheme with a battery energy storage system (BESS). Fig. 2 shows a schematic of a three-phase DVR connected to restore the voltage of a three-phase critical load. A three-phase supply is connected to a critical and sensitive load through a three-phase series injection transformer. The equivalent voltage of the supply of phase A*v*Mais connected to the point of common coupling (PCC) *v*Sa through short-circuit impedance *Z*sa. The voltage injected by the DVR in phase A*v*Cais such that the load voltage *vLa*is of rated magnitude and undistorted. A three-phase DVR is connected to the line to inject a voltage in series using three single-phase transformers *Tr*. *Lr*and *Cr* represent the filter components used to filter the ripples in the injected voltage. A three-leg VSC with insulated-gate bipolar transistors (IGBTs) is used as a DVR, and a BESS is connectedto its dc bus.

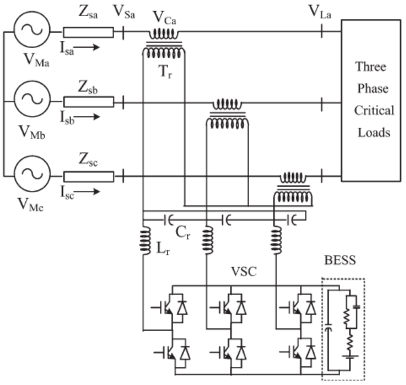


Fig. 2. Schematic of the DVR-connected system.

IV. CONTROL OF DVR

The compensation for voltage sags using a DVR can be performed by injecting or absorbing the reactive power or the real power.When the injected voltage is in quadrature with the current at the fundamental frequency, the compensation is made by injecting reactive power and the DVR is with a self-supported dc bus. However, if the injected voltage is inphasewith the current, DVR injects real power, and hence, a battery is required at the dc bus of the VSC. The control technique adopted should consider the limitations such as the voltage injection capability (converter and transformer rating) and optimization of the size of energy storage.

V. MODELING AND SIMULATION

The DVR-connected system consisting of a three-phase supply, three-phase critical loads, and the series injection transformers shown in Fig. 2 is modeled in MATLAB/Simulink environment along with a sim power system toolbox and is shown in Fig. 5. An equivalent load considered is a 10-kVA 0.8-pf lag linear load. The parameters of the considered system for the simulation study The control algorithm for the DVR shown in Fig. 3 is also modeled in MATLAB. The reference DVR voltages are derived from sensed PCC voltages (*v*sa, *v*sb, *v*sc) and load voltages (*vLa*, *vLb*, *vLc*). A PWM controller is used over the reference and sensed DVR voltages to generate the gating signals for the IGBTs of the VSC of the DVR.

The capacitor-supported DVR shown in Fig. 4 is also modeled and simulated in MATLAB, and the performances of the systems are compared in three conditions of the DVR

VI. PERFORMANCE OF THE DVR SYSTEM

The performance of the DVR is demonstrated for different supply voltage disturbances such as voltage sag and swell. The transient performance of the system under voltage sag and voltage swell conditions. At 0.2 s, a sag in supply voltage is created for five cycles, and at 0.4 s, a swell in the supply voltages is created for five cycles. It is observedthat the load voltage is regulated to constant amplitude under both sag and swell conditions. PCC voltages *vS*, load voltages *vL*, DVR voltages *vC*, amplitude of load voltage *VL* and PCC voltage *Vs*, source currents *iS*, reference load voltages *vL*ref, and dc bus voltage *v*dc are also depicted in Fig. 6. The load and PCC voltages of phase A are shown in Fig., which shows the in-phase injection of voltage by the DVR. The compensation of harmonics in the supply voltages is demonstrated in Fig..At 0.2 s, the supply voltage is distorted and continued for five cycles. The load voltage is maintained sinusoidal by injecting proper compensation voltage by the DVR. The total harmonics distortions (THDs) of the voltage at the PCC, supply current, and load voltage. It is observed that the load voltage THD is reduced to a level of 0.66% from the PCC voltage of 6.34%. The magnitudes of the voltage injected by the DVR for mitigating the same kinds of sag in the supply with different angles of injection are observed. The injected voltage, series current, and kilovolt ampere ratings of the DVR for the four injection schemes are given in Table I. In Scheme-1 in Table I, the in -phase injected voltage is *V*inj1 in the phasor diagram in Fig. 1. In Scheme-2, a DVR voltage is injection at a small angle of 30◦, and in Scheme-3, the DVR voltage is injected at an angle of 45◦. The injection of voltage in quadrature with the line

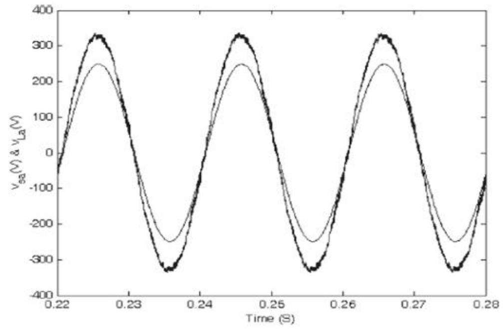
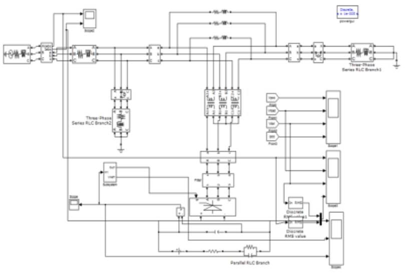
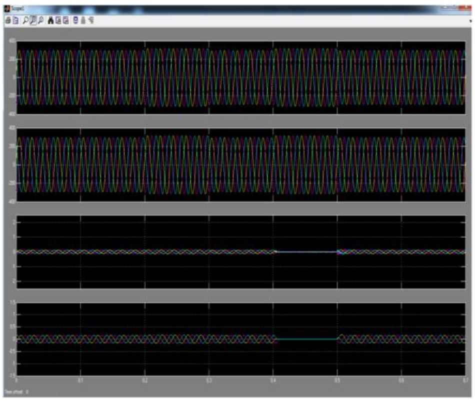


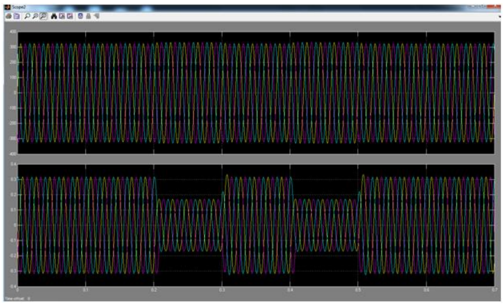
Fig. 7. Voltages at the PCC and load terminals.

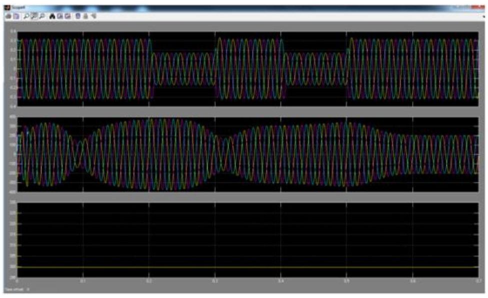
VII. MATLAB MODEL



VIII. OUTPUT WAVE FORMS







IX. CONCLUSION

The operation of a DVR has been demonstrated with a new control technique using various voltage injection schemes. A comparison of the performance of the DVR with different schemes has been performed with a reduced-rating VSC, including a capacitor-supported DVR. The reference load voltage has been estimated using the method of unit vectors, and the control of DVR has been achieved, which minimizes the error of voltage injection. The SRF theory has been used for estimating the reference DVR voltages. It is concluded that the voltage injection in-phase with the PCC voltage results in minimum rating of DVR but at the cost of an energy source at its dc bus.

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