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An Integrated VSC-Based Shunt and Series Compensators Used for Load Voltage Control Applications

1) K.SREEKANTH REDDY, 2) M.RAJU and 3)Dr. VENUGOPAL.N

KUPPAM ENGINEERING COLLEGE, KUPPAM.
Email id:reddysre@gmail.com
Ph: 08867164516, 08790874939

Abstract

In this paper, the performance of voltage-source converter-based shunt and series compensators used for load Voltage control in electrical power distribution systems has been analyzed and compared, when a nonlinear load is connected across the load bus. The comparison has been made based on the closed-loop frequency response characteristics of the compensated distribution system. A distribution static compensator (DSTATCOM) as a shunt device and a dynamic voltage restorer (DVR) as a series device are considered in the voltage-control mode for the comparison. The power-quality problems which these compensator address include voltage sags/swells, load voltage harmonic distortions, and unbalancing. The effect of various system parameters on the control performance of the Compensator can be studied using the proposed analysis. In particular, the performances of the two compensators are compared with the strong ac supply (stiff source) and weak ac-supply (non-stiff source) distribution system. The experimental verification of the analytical results derived has been obtained using a laboratory model of the single-phase DSTATCOM and DVR. A generalized converter topology using a cascaded multilevel inverter has been proposed for the medium-voltage distribution system. Simulation studies have been performed in the PSCAD/EMTDC software to Verify the results in the three-phase system.

I. INTRODUCTION

THE voltage related power-quality (PQ) problems, such as sags and swells, voltage dips, harmonic distortions due to nonlinear loads and voltage unbalancing in electrical power distribution systems, have been a major concern for the voltage-sensitive loads [1]. Load voltage regulation using VSC for different grid-connected applications has been recently attempted in [2]–[4]. With the increased use of power-electronics devices in the consumer products, the loads are becoming voltage sensitive and nonlinear in nature. Depending upon the applications, these loads are connected to the distribution system having varying voltage and power levels. Also the radial feeders of the distribution system to which these loads are connected have varying length and short circuit current (SCC) levels. This depends upon the location of the load, distribution system size, and its voltage and volt-ampere (VA) ratings. This leads to the wide variations in the thevenin's equivalent feeder impedance looking from the load side. If the load is connected at the end of the long feeder and has small short-circuit current value, it is called a weak ac supply system (or non-stiff source) [5]. These feeders have significant line impedance depending upon their length and short-circuit current value [6]. Similarly, if the load is connected close to the feeder, it is referred to as strong ac supply system (or stiff source). The line impedance of these feeders is very small or negligible

Two types of VSC-based compensators have been commonly used for mitigation of the voltage sags and swells and regulating the load bus voltage [7], [8]. The first one is a shunt device, which is commonly called DSTATCOM [9]–[12], and the second one is a series device, which is commonly called DVR [13]–[16]. In [10] and [17]–[20], these compensators can address other PQ issues, such as load voltage harmonics, source current harmonics, unbalancing, etc., under steady state to obtain more benefits out of their continuous operation. There have been a variety of control strategies proposed for load voltage control using the aforementioned two devices. For DSTATCOM, this includes reactive power compensation [21] and voltage-control mode operation of DSTATCOM [9]–[11], [17]. For DVR, it includes open-loop and closed-loop load voltage-control methods [22]. The closed-loop voltage- control mode operation of the two devices is considered best from the point of view of precise and fast control against sudden variations in the supply voltage and the load [23]. In [24], a common control strategy has been proposed for the shunt and series compensator. A detailed study of the dynamic performance of these two compensating devices controlling the load voltage under closed loop is required. This study presumes a three-phase, four-wire distribution system [5], [7], [9]–[11], in which each phase is controlled independently..In this paper, the performance of the DSTATCOM and the DVR used for the load bus voltage control have been analyzed and compared when a nonlinear load is connected across the load bus. Both of these compensators are used under closed-loop voltage-control mode. The control performance ofthe compensator and attenuation properties against perturbationshas been obtained using closed-loop frequency-responsecharacteristics. A simple output voltage feedback control and afixed switching frequency linear modulation have been used forthe operation of the VSC under closed loop. It is shown that theperformance of two compensating devices depends upon theeeder impedance. The performance study for the DSTATCOMand the DVR has been obtained for the weak and strong acsupply systems. The experimental verification of the analyticalresults derived is obtained through the laboratory model of asingle-phase distribution system, using field-programmablegate-array (FPGA)-based implementation of the controller andmodulation of the VSC. A generalized converter topology isconsidered and the modulation technique based on the cascadedmultilevel inverter has been proposed for medium-voltage distributionsystem applications [25]. Simulation studies have beenperformed to verify the results in a three-phase distributionsystem.

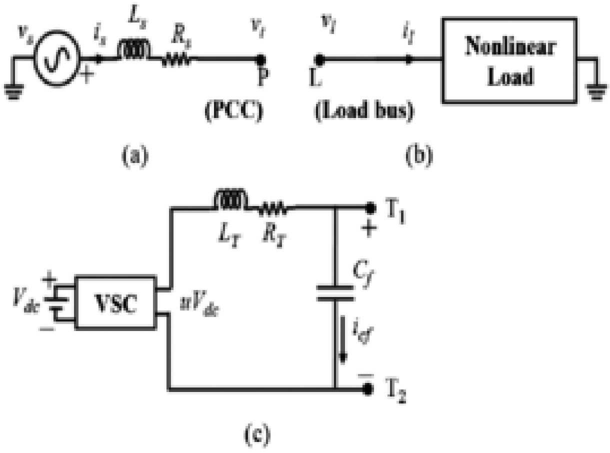


Fig. 1. Compensator structure used for load voltage control for a single-phase equivalent of a distribution system. (a) Feeder. (b) Load. (c) Compensator.

II. VSC-BASED SHUNT AND SERIES COMPENSATORS

The single-phase equivalent of a radial distribution systemis shown in Fig. 1. The feeder and load of the distribution are shown in Fig. 1(a and (b), respectively. The source vs is consideredto be the starting point of the radial feeder. The point of common coupling (PCC), represented by point P, is a particularbus of the feeder to which a nonlinear load is connected. Thevoltage at the point P is denoted by. The Thevenin's equivalentfeeder impedance is represented by inductance ls and resistance rs. Restoring the load bus voltage vl at point L under the conditions of sags and swells in the source is an essential requirementfor the sensitive loads. Also, it is required to controlthis voltage against distortions due to the nonlinear load [26].A VSC-based generalized structure of the compensator used in a single-phase distribution system is shown in Fig. 1(c). Twotypes of compensators have been considered in this paper forload voltage control of the distribution system.

In case the compensator is shunt type (i.e., DSTATCOM), theterminals P, L, T1and are joined together and T2is grounded.In case the compensator is series type (i.e., DVR), the terminalT1is connected to L and T2is connected to P. The mpensatorconsists of a VSC that is interfaced to the distribution system.

The voltageVdc represents the net dc link voltage across theVSC. The variable u is defined as the control input and representsthe high-frequency switching of the inverter that assumesdiscrete values between +1and -1, depending upon the numberof levels used in the multilevel converter topology [17], [27].The symbol Ltrepresents the equivalent inductance in the convertercircuit. The resistance Rtrepresents the equivalent losscomponent in the cmpensator. The filter capacitor Cfis connectedacross the VSC to support the output voltage and providefiltering to the high-frequency switching components of theVSC. The currents flowing through the different branches are:the source current, the load current, and the current throughthe filter capacitor Icf.

The nonlinear load considered in this paper is assumed to be abridge rectifier type with input impedance(L1ac, R1ac)[4]. Fora single-phase load as shown in Fig. 2, the output dc voltageof the bridge rectifier is fed to a resistive load R1dcsupportedby a parallel dc capacitor c1dc. This nonlinear load is calleda voltage source type and is represented by a harmonic perturbationvoltage sourceVd, where Vdis the Thevenin equivalentvoltage source of this load [11], [17], [28]. For a largedc capacitorcldc and ac inductanceLlac, theinput impedance(Llac, Rlac)approximately represents the Thevenin equivalentimpedance of this nonlinear load. The approximate equivalentof this type of nonlinear load is also shown in Fig. 2.

A. DSTATCOM Model

The single-phase equivalent circuit of a DSTATCOM-compensated distribution system is shown in Fig. 3. The VSC is used for the injection of the controllable ac voltageUVdc in order to control the load bus voltageVl under the closed loop. The dclink voltage may be self-supported by a dc-link capacitor for the case of DSTATCOM [10]. The current injected in the shunt path is denoted byish. A voltage-source-type nonlinear load as considered in Fig. 2 is connected with the Thevenin equivalent voltageVd and impedance (Llac, Rlac).

Choosing the state vectorXT=[ish icf Vt iL] and consideringthe load voltageVt as output, the following state spacerepresentation can be derived

$$\dot{x} = Ax + b_1 v_s + b_2 u + b_3 v_d$$
$$v_l = cx \quad (1)$$

where the matricesA, b1, b2, b3, c, , , , and are defined in the Appendix.

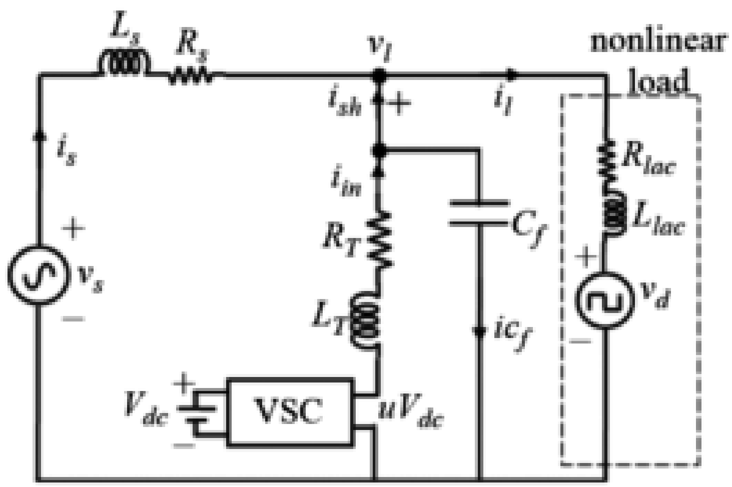


Fig.2.equivalent circuit of a D-STATCOM-compensated distribution system

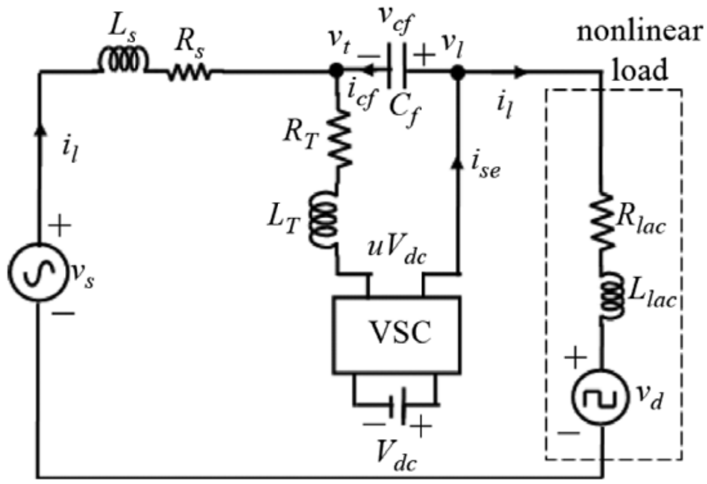


Fig.3.equivalent circuit of a DVR-compensated distribution system

B. DVR Model

The single-phase equivalent circuit of a DVR-compensated distribution system is shown in Fig. 4. In the direct control scheme presented in this paper, the DVR injects the controllable voltageUVdc in order to control the load bus voltage Vlunderclosed loop. The dc link voltage in this case may be supported by grid-connected rectifier [19] or separate energy storage [29].The current flowing through the VSC is defined as the seriescurrenti_{se}. The source current is is assumed the same as the load current in this case. The remaining system parameters and variables are the same as defined for the DSTATCOMmodel in Fig. 3.

Choosing the state vector Xt=[Vcf ise il] and considering the load voltage as output, the following state space representation can be derived:

$$\dot{x} = Ax + b_1 v_s + b_2 u + b_3 v_d$$
$$v_l = R_{lac} i_l + L_{lac}\frac{di_l}{dt} + v_d = cx + qv_s + wv_d \qquad (2)$$

where the matrices A, b1, b2, b3, cand w are defined in the Appendix.

III. LOAD VOLTAGE CONTROL AND VSC MODULATION

It has been shown for DSTATCOM in [10], [11], [17] andfor DVR in [15] that the closed-loop control is achieved usingvoltage and current feedback loops. In this paper, a simpleoutput voltage feedback control is used for the control of theload bus voltage. In this scheme, the actual load voltageVlis fed back and compared with the reference voltageV1ref.The error el so obtained is passed through the proportionalplus low-pass-filtered derivative controller [30] to produce a switching function. The -domain representation of thecontroller transfer function between the output switchingfunction Se and the input error function elis defined as

$$G_c(s) = \frac{s_e(s)}{e_l(s)} = k_1 + \frac{k_2 s}{\alpha k_2 s + 1}$$

(3)where the error function is defined as. Theconstants and are the proportiona and derivative gains, respectively. The derivative action is associated with the firstorderlow-pass filter to limit the amplification of the high-frequencynoise and disturbances. The low-pass filtering action dependsupon the filter coefficient.The switching function so obtained is modulated followingthe phase-shifted multicarrier PWM for the cascaded multilevelconverter as given in [17]. The equivalent modulation methodused with the two-level converte can be implemented as [11]for (4a)for (4b)where is a triangular carrier of suitable amplitudeand frequency. This modulation scheme leas to the VSCoperation at the fixed switching frequency, when the amplitudeof the carrier is chosen above a certain minimum amplitude[11], [17]. A small hysteresis band is introduced toavoid the multiple crossings at the intersection in (4). The modulationprocess represents the linear relation between the inputand output on the average basis. The linear gain of the modulatoris represented by [17]. The allowable limitof gain increases with an increase in switchingfrequency; therefore, the tracking characteristics improve at ahigher switching frequency [17], [31]. The output of the modulatoris delayed by the average switching delay (i.e., half theswitching period). In case of themultilevel inverter, represents the effective switching frequency [17]. The effectof the high-frequency switching due to modulation is modeled as a first-order lag. Therefore, in steady state, the modulationprocess is defined by a transfer function that consists ofa fixed gain and a delay function as(5)The complete block diagram of the load voltage control usingeither DSTATCOM or DVR is shown in Fig. 5

B. DVR MODEL

The single phase equivalent circuit of a DVR-compensated distribution system is shown in fig.4.In the direct control scheme, the DVR injects the controllable ac voltage uVdc in order to control the load bus voltage Vl under closed loop.The dc link voltage in this case may be supported by grid connected rectifier[19] or separate energy storage[29].The current flowing through the VSC is defined as the series currnt ise.The sorce current is is assumed the same as the load current il in this case.The remaining system parameters and variables as the same as defined for the DSTATCOM model in fig.3.

Choosing the state vector xT=[vcf ise il] and considering the load voltage vl as output, the following state space representation can be derived ;

$$\dot{x} = Ax + b_1 v_s + b_2 u + b_3 v_d$$
$$v_l = R_{lac} i_l + L_{lac}\frac{di_l}{dt} + v_d = cx + qv_s + wv_d \qquad (2)$$

Where the matrices A, b1, b2, b3, c, q and w are defined inthe appendix.

IV. TRACKING CHARACTERISTICS USING STEADY-STATE FREQUENCY-RESPONSE ANALYSIS

In this section, the steady-state tracking behavior of the load voltage control using DSTATCOM and DVR are discussed. Comparisons of the tracking characteristics of the two compensating devices are made with reference to the weak and strong ac supply system.

A. Weak AC Supply System

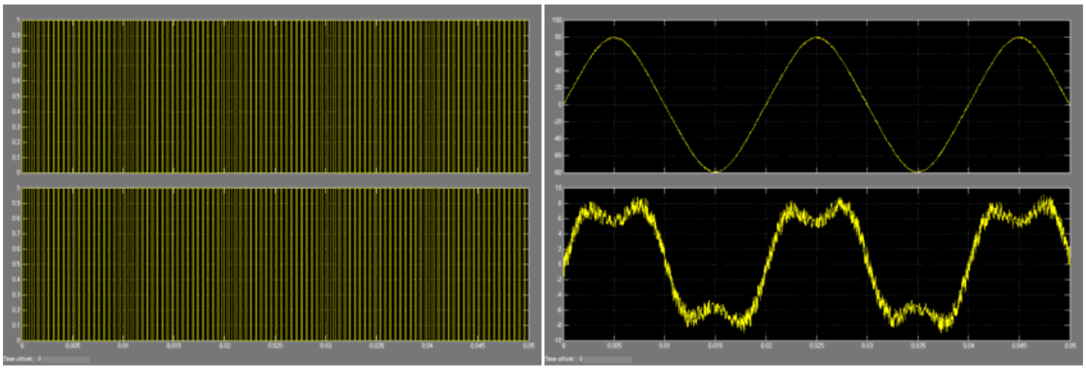
Assume a weak (or non-stiff) ac supply system. Consider the per unit system parameters of such a weak ac supply system given in Table I.

1) DSTATCOM: Let us first study the tracking characteristics of load bus voltage control using DSTATCOM. The transfer functions, , and are determined using (6)–(8), respectively. The state space model of DSTATCOM given in (1) is used for obtaining the transfer functions. Under the ideal tracking condition in (4) (i.e., high gain and zero delay in (5) corresponding to infinite switching frequency, and ideal derivative action in (3), that is,), the dominant closed-loop pole will lie close to for the closed-loop system shown in Fig. 5. Therefore, the system dynamics will be governed by the time constant. However, with practical switching devices (e.g., insulated-gate bipolar transistors (IGBTs) operating at the finite fixed switching frequency).

2) DVR: Consider now study of the tracking characteristics of the load bus voltage control using DVR for a weak ac supply system. The transfer functions, , and for the case of DVR are determined using (6)–(8), respectively. The state space model of DVR given in (2) is used for obtaining these transfer functions. Fig. 8 shows the closed-loop frequency response of the output load voltage with respect to the reference voltage for the same data as considered for the DSTATCOM earlier. The effective switching frequency and gain for the modulator (5) are considered high as for the case of the DSTATCOM. It can be seen from Fig. 8 that the tracking characteristic with theDVR is similar to that of the DSTATCOM. However, the bandwidth of the control loop in case of DVR is reduced considerably compared to that with DSTATCOM.

V. EXPERIMENTAL RESULTS

A single-phase experimental model developed in the laboratory has been used to obtain the verification of the analytical results presented in the previous section. The controller and modulation technique used in this paper is implemented in a National Instrument (NI), PXI-7831 reconfigurable input/output (RIO), field-programmable gate array (FPGA), through Lab- VIEW software-based graphical programming. The programs are downloaded on a PXI 8186, remote embedded controller. In addition, the FPGA is also programmed to generate the sinusoidal reference for the load voltage, the frequency of which is synchronized with the supply using a software-based phaselocked loop (PLL). The VSC is implemented using the Mitsubishi, Intelligent Power Module (IPM) PM50CSD120. The load voltage is fed back using LEM, voltage transducer LV25-P. The ouput for VSC based shunt and series compensators are as shown below.



In the absence of any compensation and with the distorted source voltage as shown in Fig. 14 and having a total harmonic distortion (THD) of 5.2%, the load voltage gets distorted and has a THD of 21.8% and a magnitude reduced by 10%, due to the nonlinear load and distorted supply voltage. The DSTATCOM effectively controls the load voltage against variations in the source voltage and in the presence of the harmonic components of the nonlinear load.The THD of the load voltage improves to 1.7% and controlled close to 60 V rms.

V. CONCLUSION

The performance of the VSC-based shunt and series compensators has been analyzed in voltage control mode through closed-loop frequency-response characteristics. It is shown that for the weak ac supply system, the load voltage control using DSTATCOM has large bandwidth and good attenuation in source voltage and nonlinear load perturbations. However, the DVR in this case passes high-frequency load components almost unattenuated and causes the presence of notches in the load voltage. For the case of a strong ac supply system, the DVR has good bandwidth and attenuation properties. The DSTATCOM in this case cannot control the load bus voltage. The proposed analytical results have been verified through the laboratory experimental model. The generalized converter topology based on cascaded multilevel inverter using multi-carrier phase-shifted PWM can be used for the load voltage control of an MV distribution system, following the proposed control algorithm. The results for the three-phase load voltage control have been verified for an 11-kV distribution system, using seven-level cascaded transformer multilevel converter topology, through simulations.

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