Voltage Sensorless Control Algorithm for Power Quality Improvement in Distribution Network

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Abstract— In this paper, a voltage sensorless control algorithm based on voltage estimators is used to control the DSTATCOM (Distribution Static Compensator) for a three phase four wire distribution system. The control algorithm emulates the load and DSTATCOM collectively as a balanced resistive load on the supply system. This algorithm functions as an estimator and eliminates the voltage sensor requirement. This algorithm is derived for a modified topology of DSTATCOM in the system which advantages are described in this paper. Due to simplicity of the algorithm, it can be easily implemented with reduced calculation than other complex algorithms. This algorithm is very effective in mitigating the various power quality problems like large neutral current due to unbalanced or nonlinear loads, reactive power consumption, harmonics current injection, voltage regulation in the distribution system.

Keywords— Sensorless algorithm, DSTATCOM, power quality, harmonic filter, modulating signals.

I. INTRODUCTION

DSTATCOM (Distribution Static Compensator) has been proved to be an effective device for mitigating many power quality problems. These problems arise in the distribution system due to ever increasing use of power electronics based equipment for domestic purposes. These are computers, LCD/LED, TVs, various lighting systems and electric drives and domestic loads along with switched mode power supplies, battery charging circuits etc which inject the harmonics in the supply system [1], [2]. These current harmonics distort the voltage at the other buses of the network, consume large amount of reactive power and increase the neutral current causing the neutral conductor bursting. That why standards have been made as a limit on total harmonic distortion (THD) of the current drawn from supply [4]. Use of passive and active filters for harmonic eliminations are described in [1, 2] and it is shown that DSTATCOM has excellent performance in mitigating these power quality problems.

DSTATCOM basically works to make the supply currents balanced sinusoidal with unity power factor or somewhat leading in case of voltage regulation.

These operations of DSTATCOM require that supply current, supply voltage, load current and DC link voltage to be sensed. There are many methods and techniques proposed in the literature for doing these operations by sensing all the quantities described above and there are some other techniques which are also proposed in the literature. Kummar et al. [5] have described various control algorithms for load balancing, power factor improvement in a four wire system. They also consider the effect of unbalanced supply voltages. A state feedback controlled DSTATCOM is balancing the load and compensating neutral current with non-stiff AC voltage source is described in the literature [6] to operate in a four wire system. Three single phase bridge converters are used and connected in star configuration. Load compensation capability of the DSTATCOM is also shown in the literature [7] where a diesel generator based isolated system is studied. There a three wire system is simulated with Adaline control algorithm [8] uses a different topology of DSTATCOM as the bridge has switches only in two legs and the third leg is made from the split capacitors. Moreover, the neutral current is compensated by a star/hexagon transformer. This topology reduces the control effort and also the losses of two switches. A composite observer-based control algorithm is used for power factor correction and load balancing in [9] and the neutral current is compensated using star/delta transformer. Such techniques are easy to implement as they are computational based schemes. Wu et al. [10] and Jou et al. [11] have proposed different topologies for hybrid active power filter than the conventional configuration. For a three wire system in [10] a two leg inverter is used and for a 4 wire system in [11] a three leg inverter is used. Lohia et al. [12] have proposed a special technique to balance the load currents and to compensate the neutral current with a minimum switching in a 4 leg VSC topology. These publications [7, 8], [10] and [11] have used different topologies of DSTATCOM than conventional topology and the control technique is adjusted accordingly. But there are some publications in which the system setup arrangement has been changed to implement the control algorithm [13-15].

The control techniques used are of basically two types. The method how it works are different. One method is to obtain the compensator current required to be injected which makes the supply current as desired and it operates DSTATCOM taking that as reference current for the compensator. This is called direct control of DSTATCOM.
This type of control is used in [5] and [6]. Other method is to obtain the desired supply current and operate DSTATCOM by taking that current as reference for supply current. This is called indirect control scheme of DSTATCOM [7-9]. Now in direct control, as the reference current is having all the harmonic currents so it becomes difficult to track them exactly, whereas in indirect method, the reference to be tracked and to follow fundamental frequency supply current, so it is comparatively easier in the implementation.

Keeping this in the mind and some other factors discussed later, a different system arrangement is used and based upon that a calculation based indirect control technique is proposed for single phase systems [13]. This control technique emulates the load and DSTATCOM collectively as a resistive load. It makes the DSTATCOM to act as negative inductance or in capacitive nature. In [13], used equations are simple KVL equations with supply voltage or supply current substituted according to the mode of operation to make the technique sensorless in a single phase system and in the literature [14] also a calculation based technique is proposed but the control is derived using powers instead of KVL, so that is more complex technique. Salo [15] has proposed a current sensorless technique for a current source inverter based APF and the same topology as used in the literature [13]. The derivation of control signals in [13] and in this paper is done by taking the averaged quantities. The requirements and advantages of this is described in [18] and also discussed in this paper in later sections.

In this paper, calculation based voltage sensorless control algorithm is described for a four leg DSTATCOM to mitigate power quality problems in a three phase four wire distribution system. The algorithm is derived by using a different system arrangement other than conventional ones, which leads to a simple control strategy. System arrangement has an inductor in between the source side and the load and as the DSTATCOM is compensating the harmonic currents, so the current through the inductor is only fundamental which reduces the losses than it would be there if the compensator current passes through the inductor. This is because the compensator current becomes large in some cases like large load unbalance or excessive neutral current, so this increases the losses in the inductor. Moreover, with the inductor on the supply side only one equation containing fundamental quantities is required whereas if the inductor is at the inverter output, as in conventional arrangement, then the current there is having large number of harmonics only; so one has to write several equations corresponding to the dominant harmonics. The algorithm is good in maintaining unity power factor and balancing supply currents and also in compensating the neutral current. Simulations results of the technique shows the quality of performance with such a simple technique and the effectiveness in harmonic compensation, reactive power compensation, load balancing and neutral current compensation can be seen from the results.

II. SYSTEM DESCRIPTION

System under study is a three phase four wire system. The system arrangement for the sensorless technique is shown in Fig. 1. It is different from the conventional arrangement. In conventional arrangement, the load is directly connected to the supply system and the DSTATCOM is connected in shunt to the load. Moreover, DSTATCOM is connected to the line connecting supply and load through an interfacing inductance (Lf). Thus in conventional arrangement the load voltage and source voltage are same.

But in this arrangement DSTATCOM is connected to the supply system through an inductance (Lf) and the load is connected at the output of the DSTATCOM. In this arrangement, the load voltage and the converter voltage are same. That’s why to reduce the harmonic content of load voltage to an acceptable level [4], harmonic filters are employed. These harmonic filters eliminate the higher frequency voltage components and make the load voltage near to sinusoidal.

![Fig. 1. System Configuration](image)

III. HARMONIC FILTERS

The inverter output voltage contains mostly the PWM carrier frequency range harmonics and also some lower order harmonics. This harmonics are eliminated and the load voltage THD is maintained below a limit using harmonic filters shown in Fig. 2. It consists of one low pass filter, a ripple filter and one single tuned high pass filter. The design values of filters parameters are given in Appendix A.

A. Low Pass Filter

An RLC type low pass filter is used here. Low pass filter eliminates the higher order harmonics.

Transfer function of the low pass filter with the parameters is defined as,

$$G(s) = \frac{R C s + 1}{L C s^2 + R C s + 1}$$  \hspace{1cm} (1)

The response of this filter is shown in Fig. 3. Due to the nature of the low pass filter used in Fig.3, some lower order harmonics magnitude increases which again increases the THD. To mitigate this problem another ripple filter is added to eliminate these lower order harmonics. Moreover, using low pass filter, the higher order harmonics cannot be completely eliminated, so another C-type high pass filter with additional elements to mitigate problem of resonance is added.
B. Ripple Filter

It is required to eliminate the higher order harmonics still left after the low pass filter. The frequency response is shown in Fig. 8 and explained in Appendix B.

C. High Pass Filter

It is a single tuned LC type filter. Thus it acts as a high pass filter with tuning frequency as the cut-off frequency. At high frequencies, this connection results in a wide-band filter having an impedance limited by the resistance ‘R’. Addition of resistance in parallel increases the bandwidth of the filter. This filter is required to eliminate selective dominant harmonics left after the low pass and ripple filter. High pass filter is tuned to 23rd harmonic and it attenuates this and higher order harmonics further. The frequency response is shown in Fig. 9 and explained in Appendix B.

Fig. 2. Harmonic Filter

![Harmonic Filter Diagram]

Fig. 3. Magnitude Response of Low Pass Filter

![Magnitude Response Graph]

IV. CONTROL ALGORITHM

DSTATCOM is a device which compensates the load harmonics currents, fundamental reactive power component of current, balances the supply currents under unbalanced load conditions and also compensates the neutral current in case of unbalanced load. With DSTATCOM working in the topology shown in Fig. 1, the supply currents are balanced sinusoidal, therefore the inductance is carrying balanced sinusoidal supply currents in phases and ideally zero current in neutral wire. So from this topology in which inductors are carrying supply currents instead of compensating currents as in conventional arrangement, the control can be derived which directly controls the supply currents, no need to calculate the compensating currents which is far more difficult to calculate.

Voltage Sensorless Algorithm

The inductor in this topology is connected between grid and converter; and the load is connected to the converter output directly through a filter. This makes only fundamental frequency current along with some high frequency components of little magnitude to pass through the inductor. The algorithm is derived from the KVL equation, and for control purpose it is advantageous to consider only fundamental quantities. The basic idea here is to eliminate the high frequency components from these quantities. This can be done by averaging [18]. Averaging of any quantity is done by taking the average of that quantity over a desired interval of time for the whole operation period. As it is required to eliminate the effects of the switching frequency components in the voltages and currents so the averaging is done over the interval of switching period. The averaging of the quantities in this case is implemented by passing these through a low pass filter which cut frequency is adjusted so as to eliminate the switching frequency components in the signal. This can be achieved because a low pass filter basically does averaging operation [3]. Simply writing the voltage equation between grid and converter as,

\[ v_{sa} - L_f \frac{di_{sa}}{dt} - S_x v_{dc} = 0 \quad x \in a, b, c \]  

(2)

where, ‘S’ and ‘x’ are the switching function of the converter leg and notation of three-phase system. Switching function of the converter equation is written as discussed above; its averaged quantities are used. So the above equation becomes,

\[ \overline{v_{sa}} - L_f \frac{\overline{di_{sa}}}{dt} - S_x \overline{v_{dc}} = 0 \]  

(3)

So this averaged switching function is a low frequency signal and can be easily estimated with the other averaged network quantities.

The control is designed to operate the DSTATCOM in unity power factor mode. This means that the DSTATCOM makes the current drawn from the supply to be in phase with the supply voltage. So the control is derived using this fact only, explained as,

With UPF mode of operation, the load and DSTATCOM collectively appear as a resistive load to the source. So the supply current is like as,

\[ \overline{i_{sa}} = \frac{\overline{v_{sa}}}{R_e} \]  

(4)

where \( R_e \) is the effective resistance.

In this, the value of \( v_{sa} \) will be substituted from (4) in (3).

After substitution, (3) becomes,

\[ R_e \overline{i_{sa}} - L_f \frac{\overline{di_{sa}}}{dt} - S_x \overline{v_{dc}} = 0 \quad x \in a, b, c \]  

(5)
To maintain DC link voltage a control variable has to be defined so that it controls the DC link voltage of the DSTATCOM. This variable is derived from the effective resistance and DC link reference voltage as follows,
\[ V_{dc} = \frac{R_c v_{dc}}{R_c} \]
(6)
where \( R_c \) is a gain included to compensate for current measurement gain.

Substituting the value of \( R \) from (6) in (5), and using the property of sinusoidal signal that
\[ \frac{dX}{dt} = -\omega^2 \int X \, dt \]
We get switching functions as,
\[ S_k = \frac{\int i_{sn} \, dt}{v_{dc} v_{dc}} + \frac{k_e}{v_{dc} v_{dc}} \int i_c \, dt \]
(8)

This derivation is per phase, the modulation index is obtained for that phase which supply current is taken for the calculation. Calculation of modulating signals for all the phases requires all the three phase averaged currents. The calculated modulation index is in average mode. These are compared with the carrier signal to generate pulses. Modulation signals obtained above are calculated to make DSTATCOM working in unity power factor mode, but as there are single phase loads, so neutral current also has to be compensated; source neutral current must be maintained to a small value to avoid neutral conductor bursting. As the currents are being sensed in this algorithm, the neutral current compensation can be easily implemented. The complete algorithm is shown in Fig. 4.

![Fig. 4. Voltage Sensorless Control Algorithm](image)

V. RESULTS AND DISCUSSION

The voltage sensorless algorithm discussed above is simulated in MATLAB/SIMULINK environment. Results are obtained by operating DSTATCOM in UPF mode with load balancing and neutral current compensation. Steady state performance of the algorithm is shown under nonlinear load and dynamic performance of the algorithm is shown by making the load unbalanced by removing one phase load completely. Various simulation results are described below. Simulation data is provided in Appendix.

A. Performance of Voltage Sensorless Algorithm at Nonlinear Load

Steady state and dynamic performances of the control algorithm are studied by removing a single phase load, while the system is in continuous operation and then restoring the load. The simulation results are shown in Fig. 5, where \( v_s \) is the source voltage, \( i_s \) is the supply current, \( v_{lc} \) is the load voltage, \( i_c \) is the load current, \( i_{sa}, i_{sb}, i_{sc} \) and \( i_{sn} \) are the compensator currents, \( S \) is the modulating signal, \( i_{na} \) is the load neutral current, \( i_{na} \) is the supply neutral current and \( v_{dc} \) is the DC link voltage. Here one of phase of connected load is thrown at time=2.00 s, and it is restored at 2.2 s. The results are shown that the control is able to maintain the unity power factor and balances sinusoidal currents at the source side. With the balanced nonlinear load, the neutral current is comparable to the load current and after unbalancing the neutral current further increases to a higher value; but the DSTATCOM is compensating most of the neutral current at the load end itself and a small current is flowing in the supply neutral conductor. Performance in terms of maintaining DC link voltage is also very good as there is a little hike in the voltage at the time of load throwing but it is quickly maintained by the algorithm. Harmonic spectra of supply current (\( i_s \)), load current (\( i_c \)) and voltage at PCC (\( v_{lc} \)) is shown in Fig. 6 where distortions are under acceptable limit. It includes supply current (\( i_s \)), load current (\( i_c \)) and PCC voltage (\( v_{lc} \)).

![Fig. 5. Performance of DSTATCOM with Voltage Sensorless Control Algorithm](image)
The intermediate signals of the control algorithm is shown Fig. 7. It shows the signals at different intermediate stages of the algorithm.

Fig. 7. Intermediate Signals of the Control Algorithm

VI. CONCLUSIONS

The proposed algorithm is simple and easily implementable. The performance of the algorithm confirms its effectiveness in mitigating power quality problems in distribution network. Sensorless algorithm is effective in maintaining unity power and balanced sinusoidal currents at the supply side even with unbalanced and nonlinear loads. It is also avoiding the large neutral current flowing in the neutral wire, thereby removing the neutral conductor bursting problem in the distribution system. The problem with this arrangement is that the load is directly connected to the output of the inverter which demands extra filters. Overall cost is exempted from the cost of the voltage sensors. Simulation results confirm that overall performance of the control algorithm is good and satisfactory even with such a simple algorithm.

APPENDIX A

Three phase Supply: 415 V, 50 Hz with supply inductance \( L_s = 0.1 \text{mH} \); Series interfacing inductor \( L_f = 5 \text{mH} \). Nonlinear load (three single phase diode bridge rectifiers connected RL load): \( R = 10 \Omega \) and \( L = 60 \text{mH} \); DC link Voltage: 700 V for voltage sensorless algorithm; DC link capacitor = 5000 \( \mu \text{F} \); Switching frequency \( f_s = 10 \text{kHz} \); Parameters of filters: For low pass filter, \( L_1 = 1 \text{mH} \), \( R_1 = 4 \Omega \), \( C = 40 \mu \text{F} \); for ripple filter \( R_2 = 4 \Omega \), \( C_2 = 20 \mu \text{F} \) and for high pass filter, \( C_3 = 5.5 \mu \text{F} \), \( L = 3.5 \text{mH} \), \( R = 250 \Omega \). Proportional and integral gains used in DC link voltage control: \( K_p = 1 \) and \( K_i = 2 \).

APPENDIX B

Ripple Filter: For the filter parameters described in Appendix A, the frequency response is shown in Fig. 8.

High Pass Filter: A damped high pass filter of 415V, 50Hz, tuning frequency=1150Hz (23rd harmonic), reactive power at fundamental frequency=100 VAr (kept small as DSTATCOM will take care). These requirements correspond to the values given in Appendix A. The filter parameters are calculated using basic filter design methods described in [19]. Further the response of the high pass filter is shown in Fig. 9.
REFERENCES


