Flicker Mitigation Approach Based on Three-Level STATCOM

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***Abstract*—This paper presents an effective flicker mitigation approach using three-level STATCOM. In this model, fluctuations and other power quality problems caused by large time-varying loads, like arc furnaces, have been mitigated. Three-level inverter based STATCOM is applied to reduce this kind of disturbances. With the availability of recent forced-commutated components, such as IGBT and GTO, a STATCOM becomes possible to be implemented as an efficient means to reduce voltage fluctuations causing flicker. Based on the three-level digital modeling of STATCOM which is equipped with a phase locked loop, both large time-varying and short time-varying power quality phenomenon would be mitigated. The simulation results show that the presented method is both satisfactory and consistent with expectation.**

***Keywords*— Light flicker, STATCOM, Three-level Inverter and Power Quality**

I. INTRODUCTION

Power quality is the set of limits of electrical properties that allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly with that electric power. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power.

The electric power industry comprises electricity generation (AC power), electric power transmission and ultimately electricity distribution to an electricity meter located at the premises of the end user of the electric power. The electricity then moves through the wiring system of the end user until it reaches the load. The complexity of the system to move electric energy from the point of production to the point of consumption combined with variations in weather, generation, demand and other factors provide many opportunities for the quality of supply to be compromised. One of the power quality problems is the flicker [12].

Flicker is rapid visible changes of light level. Definition of the characteristics of voltage fluctuations that produce objectionable light flicker has been the subject of ongoing research. Flicker is addressed as random or repetitive variations in the RMS voltage between 90 and 110% of nominal. This phenomenon is always caused by arc furnaces.

The source of this is the voltage drop generated over the source impedance of the grid by the changing load current of an equipment or facility. These fluctuations in time generate flicker. The effects can range from disturbance to epileptic attacks of photosensitive persons. Flicker may also affect sensitive electronic equipment such as television receivers or industrial processes relying on constant electrical power [11].

In principle, all shunt-type controllers inject additional current into the system at the point of common coupling (PCC). An impedance of the shunt controller, which is connected to the line voltage, causes a variable current flow, and hence represents an injection of current into the line.

As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power.

The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power capability from the generator to the load, which is required to improve the steady-state transmission characteristic as well as the stability of the system.

The shunt controller basically consists of three groups:

1. Static var compensator (SVC)
   1.1. Thyristor-controlled reactor (TCR) and thyristor-switched reactor (TSR)
   1.2. Thyristor-switched capacitor (TSC)
2. Static synchronous compensator (STATCOM)
3. Static synchronous generator (SSG) or STATCOM with energy-storage system (ESS)

The SVC absorbs or generates controllable reactive power by synchronously connecting inductor or capacitor banks in and out of the power network. As a result, the SVC is too slow to respond to fast transient problems. In addition, the compensated reactive power is dependent on system parameters. The compensated capacity of the TSC, for example, is indirectly proportional to the square of the line voltage [13].

To date, CMC-based STATCOM has only just begun to be explored. This technology is relatively new. A complete

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control system for STATCOM applications basically consists of two main parts: external and internal controls. Generally, the external control depends on the power system network to which the STATCOM is connected. Meanwhile, the internal control mainly depends on the VSC topologies. An ideal internal control should instantaneously respond to a given command, which is generated by the corresponding external controller. Different VSC based STATCOMs can be operated with the same external control as long as they are connected to the same problematic power network. In the past two decades, several hundred publications have discussed STATCOM external controls, and several effective control strategies are now mature and have been applied in the field [14-17]. On the other hand, the research on the internal control for the CMC-based STATCOM is relatively new. Three major challenges, which have yet fully investigated, have made this research area very attractive.

This paper as follows. Theoretical consideration of modeling the STATCOM is presented in next section. Section III modeling principles and equations are addressed. Simulation results are presented in section IV and conclusion of this paper is conducted in last section.

II. THEORETICAL CONSIDERATIONS

Seen from the STATCOM converter, the power system is represented as an equivalent Thevenin voltage Vs with the equivalent Thevenin reactance Xs. All load changes in the power system can simply be viewed as change in data of Vs and Xs [4]. The simplified three-phase version of the STATCOM circuit is shown in Fig. 1.

The Thevenin voltages are denoted by $[v_s] = [v_{sa}, v_{sb}, v_{sc}]^T$, and the injected currents from STATCOM are denoted by $[i_t] = [i_{ta}, i_{tb}, i_{tc}]^T$. The equivalent Thevenin impedance is denoted by R_s and wL_s; the reactance of coupling transformer is denoted by wL_t; where the resistance R represents the switching and other losses of the STATCOM.

The loop equation for the circuit is:

$$v_{t.abc} = v_{s.abc} + R_s i_{t.abc} + L_s \frac{di_{t.abc}}{dt} \quad (1)$$

The voltage and current are decomposed into d-q coordinates to analyze the reactive/active power flows [5]. Considering the synchronous characteristic of the transmission line voltage v_t, we analyze the circuit with the synchronous

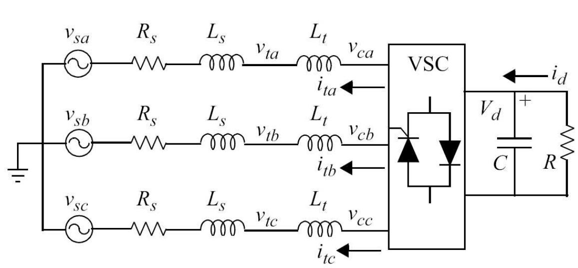


Fig. 1 Simplified three-phase STATCOM model

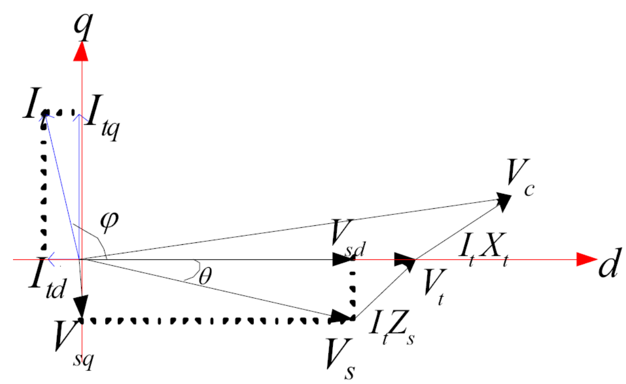


Fig. 2. Phasor diagram of STATCOM circuit

rotating reference frame. In the synchronous rotating reference frame, d-axis is defined to coincide with the instantaneous voltage vector of transmission line voltage v_t, while the q-axis is in quadrature with it. The injected current it is decomposed into i_{td} and i_{tq} which represent the instantaneous active current and instantaneous reactive current components [5].

The transformation matrix K of the synchronous rotating reference frame is:

$$K = \frac{2}{3}\begin{bmatrix} \cos(\omega t+\theta) & \cos(\omega t+\theta-2\pi/3) & \cos(\omega t+\theta+2\pi/3) \\ \sin(\omega t+\theta) & \sin(\omega t+\theta-2\pi/3) & \sin(\omega t+\theta+2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (2)$$

Where:

$$\begin{bmatrix} v_{sd} & v_{sq} & 0 \end{bmatrix}^T = K\begin{bmatrix} v_{sa} & v_{sb} & v_{sc} \end{bmatrix}^T \quad (3)$$

$$\begin{bmatrix} v_{td} & v_{tq} & 0 \end{bmatrix}^T = K\begin{bmatrix} v_{ta} & v_{tb} & v_{tc} \end{bmatrix}^T \quad (4)$$

$$\begin{bmatrix} i_{td} & i_{tq} & 0 \end{bmatrix}^T = K\begin{bmatrix} i_{ta} & i_{tb} & i_{tc} \end{bmatrix}^T \quad (5)$$

In eq. (4), $v_{td} = v_t$, $v_{tq} = 0$

The phasor diagram is shown in Fig. 2.

A. *Model of STATCOM*

With the transformation of K, eq. (1) is transformed into:

$$R_s\begin{bmatrix} I_{td} \\ I_{tq} \end{bmatrix} + L_s\begin{bmatrix} \frac{dI_{td}}{dt} \\ \frac{dI_{tq}}{dt} \end{bmatrix} - \begin{bmatrix} 0 & \omega L \\ -\omega L & 0 \end{bmatrix}\begin{bmatrix} I_{td} \\ I_{tq} \end{bmatrix} = \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} - \begin{bmatrix} V_t \\ 0 \end{bmatrix} \quad (6)$$

Using the Laplace transformation,

$$R_s I_{td} + sL_s I_{td} - \omega L I_{tq} = V_{sd} - V_t \quad (7)$$

$$R_s I_{tq} + sL_s I_{tq} - \omega L I_{td} = V_{sq} \quad (8)$$

From eq. (7), we get:

$$I_{td} = \frac{V_{sd} - V_t}{R_s + sL_s} + \frac{\omega L}{R_s + sL_s} I_{tq} \quad (9)$$

Placing eq. (9) into eq. (8), give

$$V_t = \frac{(R_s + sL_s)^2 + (\omega L)^2}{\omega L_s} I_{tq} + V_{sd} - \frac{R_s + sL_s}{\omega L_s} V_{sq} \quad (10)$$

Eq. (10) is the transfer function of the STATCOM model.

B. Model of the VSC

From the AC side, a hysteresis current controlled VSC can be viewed as a controllable current source. The output current of the VSC is regulated by the reference current. The input reference current is usually a sine wave at utility frequency, while the output current tracks it within the limits of the tolerance band. Neglecting the small harmonic components at comparatively high frequencies, the output current can be viewed to be the same as the reference current. With this assumption, it is possible to analyze the power flow behavior of the VSC [6]. Seen from the transmission line, the input active power of the VSC at the AC side can be calculated from:

$$P_{ac} = \sum v_t i_t = \frac{3}{2} V_t I_{td} \quad (11)$$

The active power of the VSC on the DC side is:

$$P_{dc} = \frac{V_d^{\,2}}{R} + V_d C \frac{dV_d}{dt} \quad (12)$$

Assuming no switching or other power losses within the converter,

$$P_{dc} = P_{ac} \quad (13)$$

To analyze the small signal disturbance response, V_t is assumed as regulated stable. Using ΔI_{td} and ΔV_d to represent the small signal disturbances, eq. (13) is transformed into:

$$\frac{3}{2} V_t \Delta I_{td} = \frac{2V_d \Delta V_d}{R} + V_d C \frac{d\Delta V_d}{dt} \quad (14)$$

After using Laplace transformation, eq. (14) is transformed into:

$$\frac{\Delta V_d(s)}{\Delta I_{td}(s)} = \frac{3V_t/2}{2V_d/R + sCV_d} \quad (15)$$

Hence, Eq. (15) is the transfer function of the VSC model.

III. STATCOM MODELING

This section details the modeling of a three-level based inverter in EMTP-RV. A three-level inverter is modeled which enables an effective doubling of the switching frequency compared with a two-level design. This allows for a reduction of one-half of the switching frequency while maintaining the same harmonic content.

A. Three Level Inverter

The three-level topology was first introduced in the late 1970's and possesses the advantage that it has the same waveform quality as a two-level inverter converter operating at twice the switching frequency.

The three-level voltage source converter differs from conventional voltage source converters in that it has four self-commutated switches in each leg instead of the traditional two. In addition to having anti-parallel diodes across each switch, the converter also has a diode between the midpoint of the upper and lower arms and the neutral point.

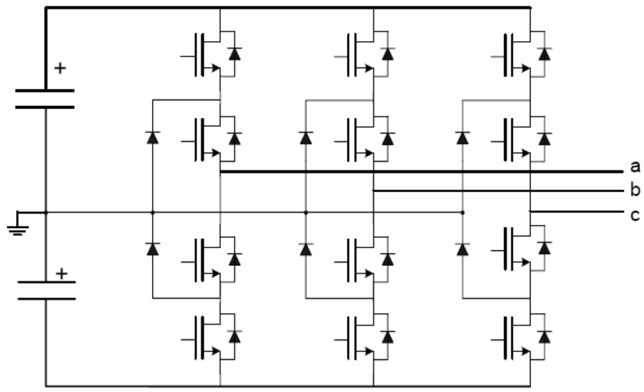


Fig. 3 Three-level voltage source converter

This design enables the converter to switch not only between the upper and lower dc voltages but it allows the output to be zero as well. Using this feature and a modification of the gating pulse generation, a better voltage waveform can be produced for the same switching frequency. This makes it an attractive option for high power applications where switching losses is a major concern.

B. Advantages and Disadvantages

As it mentioned above, an effective doubling of the switching frequency makes this topology useful for high power applications namely, motor drives, uninterruptible power supplies (UPS), and synchronous compensators such as STATCOM. However, the arrangement leads to various technical challenges that do not occur with the conventional type of inverter. Firstly, the generation of the three level inverter PWM waveforms is somewhat different since it requires four gating signals instead of simply two. Various methods have been developed which use modified PWM, as well as more complicated methods utilizing space-vector modulation [7-8]. Another of the difficulties that has been identified is neutral point potential unbalance which invariably results whereby the voltages across the upper and lower capacitors can differ significantly. This issue must be considered in the generation of the gating signals in order to prevent undesirable operating characteristics.

C. Three level modulation principle

Although there are addressed many complicated modulation schemes for three level VSCs, a modified PWM scheme has been implemented here for its simplicity. The algorithm follows from conventional SPWM and although it is more simplified by nature, its performance does not differ significantly from more in depth schemes. The PWM generation produces four gating signals, one for each switch in a given leg. The four combinations of switching logic and the resulting output voltages are given below in Table 1. From the Table, the generation of the four PWM signals using triangular carriers can be determined.

Table 1: Switching logic and output voltage

SU1	SU2	SL1	SL2	V_{out}
0	0	1	1	$-V_d/2$
0	1	1	0	0
1	1	0	0	$V_d/2$

The PWM signals are produced using two triangular signals: starting from a conventional triangular carrier, two different offsets of opposite sign are added to the triangular waveform to give the required carriers. Then, the two new carrier signals are compared with the reference voltage waveform and the output as well as its inverse is used for the various gating signals. In order to deduce which outputs correspond to which gating signals one simply refers to Table 1. The figures of the reference voltage, the triangular carrier and the desired output voltages are given below.

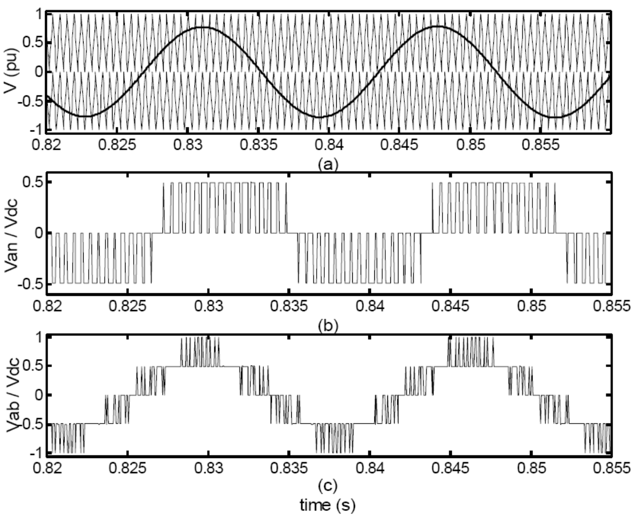


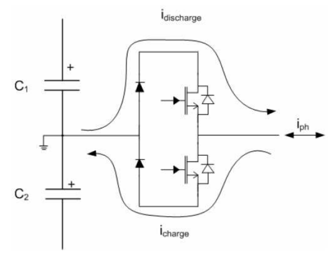
Fig. 4. (a) Reference voltage with triangular carriers (b) three level output line to ground voltage and (c) line to line voltage

D. *Neutral Point Voltage Control*

As compared with the conventional two-level VSC, a multilevel VSC (ML–VSC) configuration is advantageous for STATCOM realization [4]–[7] since it provides 1) higher ac-side voltage levels and 2) improved waveforms in terms of harmonic distortion.

Among various ML–VSC configurations [10] (i.e., the neutral-point clamped (NPC), flying capacitor, and separated dc source), the NPC–VSC offers superior performance and has been widely accepted for high-power applications [8], [9].

The neutral point unbalance is a problem which results in three-level inverter when the neutral point is connected to charging current for longer periods than to discharging currents (or vice-versa). Although the dc voltage regulator works properly, the inequality between charging and discharging neutral point current results in an unbalance between the dc voltage across the upper and lower capacitors. This is an undesirable characteristic since even if the converter is properly modulated the resulting output waveform becomes asymmetric about the x-axis and consequently, similar distortion results in the line currents. Therefore, it is imperative that a neutral point balancing algorithm be used in order to limit the unbalance to a small margin, for instance (1-2) %.



i_{ph}	ΔV_{C1}	ΔV_{C2}	$\Delta(V_{C1}-V_{C2})$
Charge	< 0	> 0	< 0
Discharge	> 0	< 0	> 0

Fig. 5 Neutral point connection and resulting change in capacitor voltages

There exist various algorithms for neutral point balancing including control of neutral point connection [9], space-vector modulation techniques [8], and control of the negative sequence power for higher level converters [6]. In this case, the neutral point connection time is controlled since the PWM scheme is easily modified and the concept is relatively straightforward. In order to understand the principle let us consider the case of how the neutral point potential is charge or discharged. As previously mentioned, the neutral point potential is changed when it is connected to the one of the phases. This results when the uppermost and lowermost switches are not on. The two innermost switches are gated and the neutral point diodes are forced to conduct. The direction of the current in the corresponding leg determines whether the neutral point potential increases or decreases.

In an NPC that operates based on the modified PWM, each switching mode can impact the dc-side neutral point voltage of the VSC [9]. The impact of switching vectors on the dc-side neutral point voltage of the NPC are given in Table I. Table I shows that SL1s and SL2s have opposite effects on the neutral point voltage. By selecting a switching pattern that includes vectors from both SL1s and SL2s, the neutral point voltage is controlled.

IV. SIMULATION RESULTS

In order to validate the proposed neutral point voltage control system, computer simulation using the EMTP-Works power system package is carried out with the main parameters: line-to-line voltage V_{pcc}=500kV, STATCOM transformer voltage, $V_{STATCOM}$=13.2 kV, system frequency, f= 60 Hz, switching frequency, f_s = 990 Hz, dc link capacitance, C_{dc}=100E-03 F.

The three-phase simulated system is based on the control scheme presented above. Gate signals for three legs are generated from control system equipped with PLL. The STATCOM output phase voltage and filtered output line voltage are shown in Fig. 6 and 7 respectively.

It can be seen that simulation results confirm the postulated issue in mitigation of voltage flicker. Active and reactive power from STATCOM terminal also illustrates in Fig. 8.

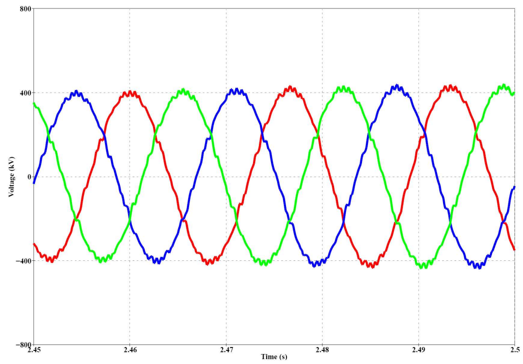


Fig. 6. Filtered voltage at PCC

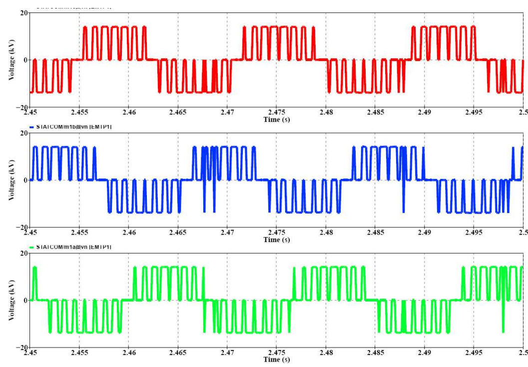


Fig. 7. Output voltage correspondence with the gate control signals

V. CONCLUSION

In order to counteract a light flicker mitigation; the neutral point connection of the phase which will contribute further to the imbalance is omitted. This is done by utilizing traditional two-level modulation for that phase only. Since neutral point unbalance does not occur with large frequency for a 1% tolerance band and due to the fact that only one phase is modulated using two-level PWM, there is not a significant reduction in the effective switching frequency. The proposed three-level inverter is implemented to refine the output voltage of point of common coupling. Simulation results show that the presented method is both satisfactory and consistent with expectation.

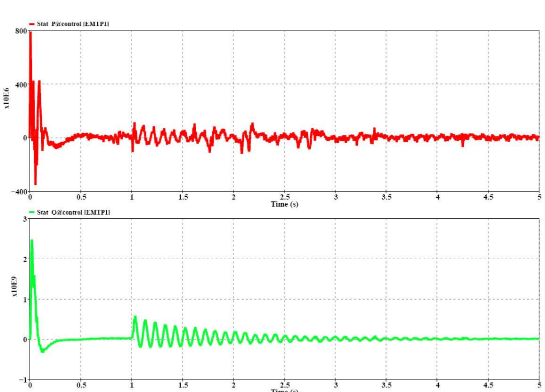


Fig. 8. Active (red) and reactive (green) delivery at PCC

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