SVM-BASED HYSTERESIS POWER CONTROLLER BY USING DIRECT POWER CONTROL FOR DSTATCOM IN ORDER TO VOLTAGE FLICKER MITIGATION

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Abstract-Distribution static synchronous compensators (DSTATCOMs) are viable solution for improving power quality in distribution systems, including mitigation for temporary interruptions, voltage dips, harmonics and voltage flicker. This paper, a space vector modulation (SVM) based hysteresis power controller (HPC) for the pulse width modulated inverter is proposed. The proposed technique utilizes all the advantages of the HPC and SVM technique. Conventional DSTATCOMs are implemented using two cascaded loops, an ac current control loop and a dc-bus voltage loop. This paper implements an alternative control structure based on the simultaneous control of line current and dc-link voltage by means of instantaneous power control. The instantaneous real and imaginary power calculation is derived and explained. Requirements for flicker and harmonic mitigation are identified. The controller is implemented using two hysteresis comparators and an optimum switching table. The features of the used technique are illustrated by means of simulation results. Advantages include a simple and robust control structure, and better tracking of load fluctuations and/or harmonics.

Keywords: **Direct power control, DSTATCOM, Flicker mitigation, SVM-based hysteresis power controller, Arc Furnace**

I. INTRODUCTION

Large industrial loads, such as electrical arc furnaces, cause harmonic voltage distortion and voltage fluctuations at the Point of Common Coupling (PCC) with other loads. Distribution static synchronous compensators (DSTATCOM), based on PWM voltage sources converters, are becoming a viable solution for improving power quality in distribution systems, including mitigation of short term interruptions, voltage dips, harmonics and flicker.

The DSTATCOM injects a compensating current, of variable magnitude, phase and frequency components, at the PCC. This injected current is reactive, emulating at fundamental frequency an inductive or a capacitive reactance. Energy storage is therefore not required.

Conventional PWM DSTATCOMs use a cascaded control scheme. The inner current loop generates harmonic and reactive current components, and the outer loop regulates the dc bus voltage. Typically, the inner current loop is as fast as the PWM pattern generation will allow. However, the response time of the outer voltage loop is longer, and the capacitor must have sufficient energy storage capability to maintain a constant dc bus voltage. Conventional carrier or space vector techniques are typically used as modulators and pattern generators for the Pulse Width Modulated (PWM) inverter.

A number of new techniques have recently been proposed for the control of PWM converters [1][7]. Issues addressed are the reduction of the number of sensors, alternate modulation schemes and the integration of control and modulation functions. The latter scheme has the advantage of faster response times, due to the elimination of the intermediate PWM pattern generation step, the possibility of controlling simultaneously more than one variable, a possible reduction of the dc bus energy-storage requirements. Such a scheme, based on the control of power, rather than current and voltage, is used in this paper, as described in Section II. The inherent fast dynamic response associated with the application of the concept of direct power control is demonstrated. The paper formulates the appropriate power terms for DSTATCOM implementation (Section III), and presents an appropriate approach to derive the optimal switching table based on the instantaneous power theory (Section IV). The features of the used and proposed technique are illustrated by means of simulation results (Section V).

II. DESCRIPTION OF THE USED SYSTEM

The inverter of DSTATCOM, Fig. 1, is a standard three phase two level inverter. The arc furnace is modeled as a time-varying modulated resistance. When this circuit is in operation, the time-varying load results in fluctuating load currents. Depending on the impedance of the line reactor, the point-of-common coupling (PCC) will see a voltage fluctuation, or voltage flicker. The voltage amplitude modulating frequency is in the range of 5 to 15 Hz [4].

To compensate the fluctuating load current, the conventional control method is to use the current control approach [5-6], and modulate the infect current to eliminate current and voltage fluctuations. The used direct power

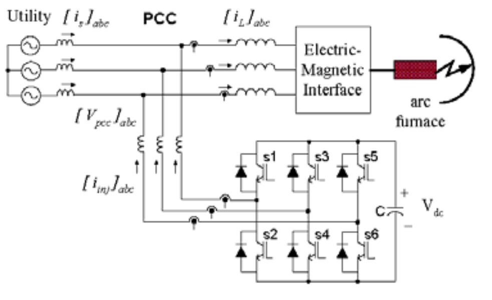
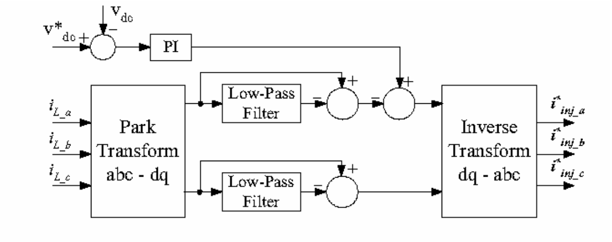
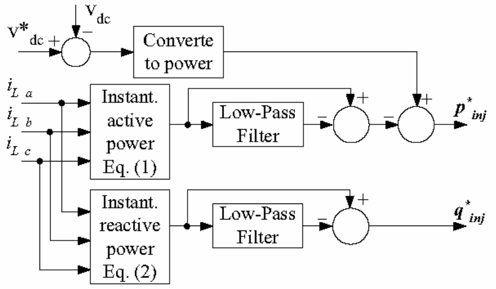


Fig. 1 The power circuit of the three-phase DSTATCOM with timing varying arc furnace load.

control and the conventional current control method are quite different in reference generation and control loop structure. Using simplified blocks, the different control reference generation schemes are shown in Fig. 2 and the different control loop structures are illustrated in Fig. 3.

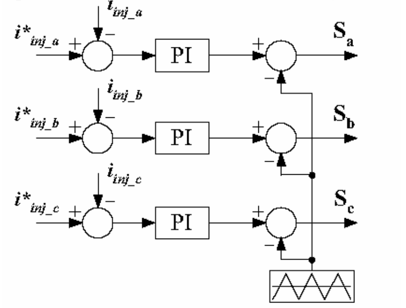


(a) Current reference generation scheme for the conventional control method.

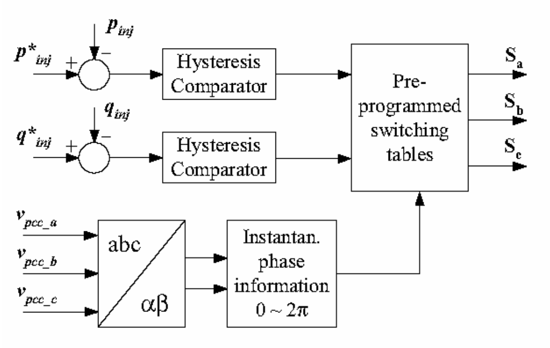


(b) Used instantaneous power reference generation scheme.

Fig. 2 The comparison of different control reference generation schemes.



(a) Conventional current control loop



(b) Used instantaneous power control structure.

Fig. 3 The comparison of different control structure and PWM methods.

The used control focus the instantaneous real power p and the instantaneous imaginary power q terms to be constant on the source side

III. THE THEORY OF INSTANTANEOUS POWER IN THREE-PHASE SYSTEMS

Conventionally, active power and reactive power in three phase circuits are defined on the basis of average values under steady state conditions.

The instantaneous power theory [2] gives a generalized definition of instantaneous real and imaginary power, which is valid for sinusoidal or non-sinusoidal, balanced or unbalanced, three-phase power systems with or without zero sequence currents and/or voltages. In this paper, only three - phase three-wire power systems are considered, the instantaneous power quantities are redefined according to the power systems of concern, and their relationships are clarified.

To deal with instantaneous voltages and currents in three-phase circuits mathematically, it is convenient to express their values in orthogonal $\alpha-\beta$ coordinates.

The instantaneous real power of the three-phase circuit can be defined as:

$$\begin{aligned} p &= v_\alpha i_\alpha + v_\beta i_\beta \\ &= v_a i_a + v_b i_b + v_c i_c \end{aligned} \tag{1}$$

instantaneous The imaginary power is defined as

$$\begin{aligned} q &= v_\beta i_\alpha - v_\alpha i_\beta \\ &= -\frac{1}{\sqrt{3}}\left(v_a\left(i_b-i_c\right)+v_b\left(i_c-i_a\right)+v_c\left(i_a-i_b\right)\right) \end{aligned} \tag{2}$$

The instantaneous real power p is the conventional instantaneous power, because it is defined as the sum of products of the instantaneous voltages in one axis and the instantaneous currents in the same axis. On the other hand, the instantaneous imaginary power q is not instantaneous power, because it is obtained by subtracting the two products of the instantaneous voltages in one axis and the instantaneous currents not on the same axis, but on the perpendicular axis. Accordingly, q can not be dealt with as a conventional electrical quantity.

In a balanced sinusoidal three-phase power circuit, the numerical value (magnitude and sign) of the instantaneous real power is constant, and it coincides with three times the conventional active power per phase. Furthermore, the numerical value (magnitude and sign) of the instantaneous imaginary power is also constant, and is numerically equal to three times the conventional reactive power per phase. Therefore, we can say the instantaneous imaginary power q represents the magnitude and sign of the conventional reactive power under this condition. However, the instantaneous imaginary power is quite different in definition and physical meaning from the conventional reactive power based on the average value concept.

In a unbalanced three-phase power system, or a distorted three-phase system caused by nonlinear loads, both the instantaneous real power and instantaneous imaginary power are no longer constant, and are expressed as two components (de values and ac values) respectively

$$p = \bar{p} + \tilde{p} \qquad q = \bar{q} + \tilde{q} \tag{3}$$

where $\bar{p}$ is the average active power delivered from the source to the load, and it is referred to as the active power associated with the positive-sequence components of the source voltage and load current. $\bar{q}$ is the average reactive power circulating between the phases. It is caused by the positive sequence components of the source voltage and load current and does not represent any power transferred from the source to the load. Rather it increases the line current amplitude and the associated losses. $\tilde{p}$ is the power ripple caused by negative sequence components and harmonics, this part of the power ripple corresponds to power oscillation between the source and the load, although its average is zero. $\tilde{q}$ is the power ripple caused by negative sequence components and harmonics, this part of the power ripple corresponds to power oscillations between phases, and its average is zero.

IV. THE SWITCHING TABLE OF PWM CONVERTERS

Two hysteresis comparators are used for control purposes. The instantaneous power of the converter varies within the hysteresis band. Therefore, this type of control is equivalent to averaged waveform synthesis. This way of control is named SVM-based hysteresis power control.

A. Determination of Switching Sectors

One of the waveform synthesis methods is to divide the $\alpha-\beta$ plane into six sectors separated by the six voltage space vectors, which is commonly used in space vector modulation. In order to track the instantaneous power reference, an alternative sector division method is to rotate the sector position by $\pi/6$, in which the sectors are centered around the space vectors.

Although the six-sector method can track the instantaneous power reference at high switching frequency, the converter instantaneous power may exceed the hysteresis boundary in the case of low switching frequencies.

As another modified scheme, the sectors are divided into twelve sectors, as shown in Fig. 4. The phase angle corresponding to each sector in the stationary $\alpha-\beta$ co-ordinates is expressed as

$$(\pi/6)(n-1) < \theta_n < (\pi/6)n \qquad n = 1,2,\ldots,12 \tag{4}$$

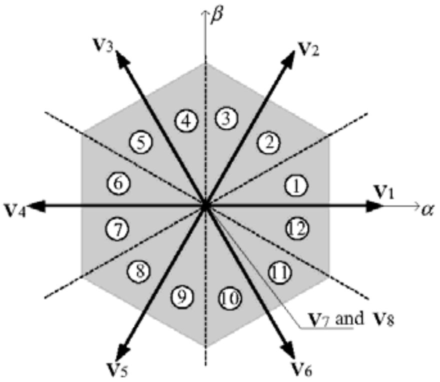


Fig.4 The twelve-sector division method to determine the switching vectors

B. Derivation of the Switching State Table

Instantaneous real and imaginary power control is achieved during a time interval Δt, by applying an appropriate voltage space vector that will drive the change of the instantaneous power in the desired direction. The influence of each voltage vector (V1-V8) on the instantaneous real and imaginary power is different, and results in different control dynamics. In direct power control, the instantaneous active power command p* is

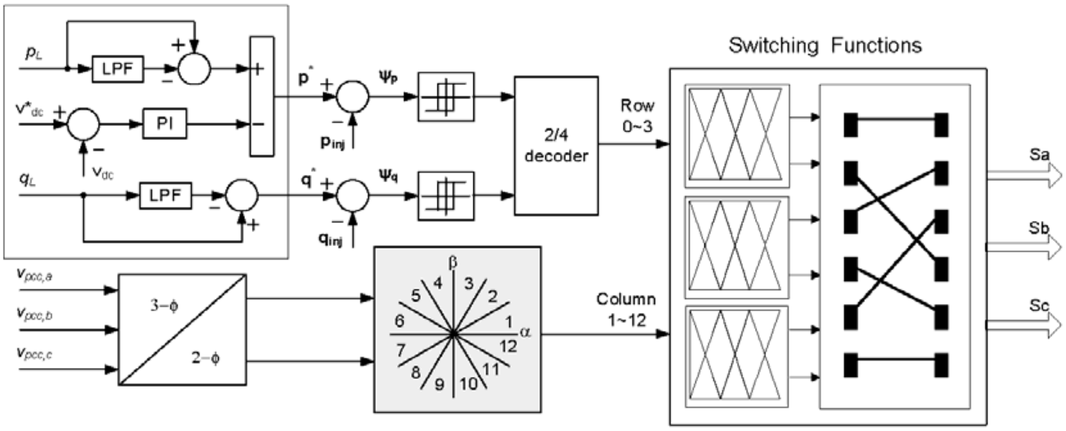


Fig. 5 Block diagram for direct power control of the three-phase DSTATCOM

generated based on the instantaneous active power ripples drawn by the non-linear load, plus the power requirement of the dc-bus voltage control loop. The instantaneous reactive power command q* equals to the instantaneous reactive power ripples consumed by the nonlinear load. The power terms of the nonlinear load are expressed as,

$$p_L = v_{pcc,a} i_{L,a} + v_{pcc,b} i_{L,b} + v_{pcc,c} i_{L,c}$$
$$q_L = -\left(v_{pcc,a}\left(i_{L,b} - i_{L,c}\right) + v_{pcc,b}\left(i_{L,c} - i_{L,a}\right) + v_{pcc,c}\left(i_{L,a} - i_{L,b}\right)\right) / \sqrt{3}$$

The power control references are obtained by extracting the ripples from the load power terms. On the other hand, the instantaneous power terms injected by the active filter are defined as,

$$p_{inj} = v_{pcc,a} i_{inj,a} + v_{pcc,b} i_{inj,b} + v_{pcc,c} i_{inj,c}$$
$$q_{inj} = -\left(v_{pcc,a}\left(i_{inj,b} - i_{inj,c}\right) + v_{pcc,b}\left(i_{inj,c} - i_{inj,a}\right) + v_{pcc,c}\left(i_{inj,a} - i_{inj,b}\right)\right) / \sqrt{3}$$

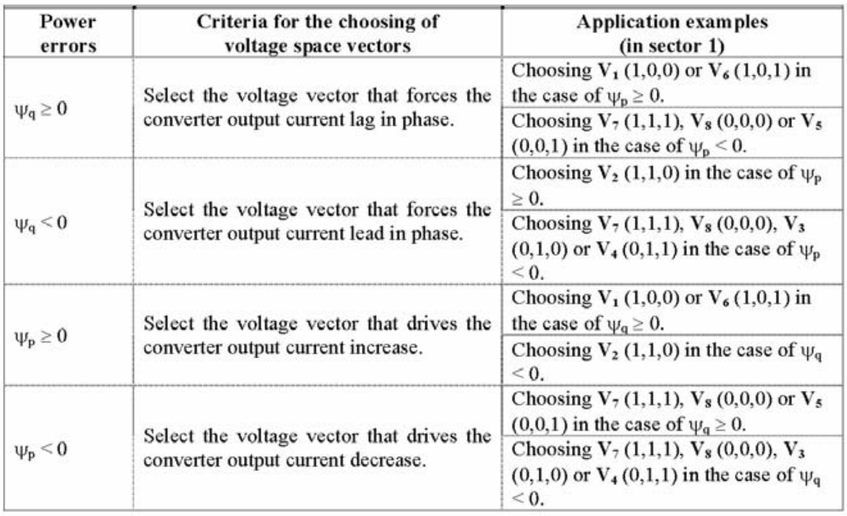
After compensation, the ac system provides only the balanced and average power portion drawn by the nonlinear load, and the DSTATCOM supplies the instantaneous power ripples drawn by the nonlinear load. If the DSTATCOM has a spare power injection capability, it can also inject all of the reactive power required by the load, including both the average reactive power component and the reactive power ripples, and a unity power factor is accomplished at the utility side in this case. The block diagram of the direct power control system is shown in Fig. 5. The instantaneous power terms of the nonlinear load and those of the DSTATCOM are inputs to the hysteresis comparators. After a two-to-four decoder, the comparator output determines the row value of the switching table. The column value is the sector number where the voltage vector is currently residing and is divided into 12 segments. By applying an appropriate switching vector to the PWM power converter, the change of the converter instantaneous power can be driven to the desired direction. The voltage space vector can be taken from one out of eight possible positions (including six non-zero vectors and two zero vectors). The influence of each voltage vector (V1 - V8) on the instantaneous active and reactive power flow is different and results in different control dynamics. The general selection criteria of the converter switching vectors are summarized in Table I. By applying the operation principles to the twelve sectors in general cases, a two-dimensional switching state table is derived in Table II. During the, implementation, the switching functions Sa, Sb and Sc are provided by the look-up table that is stored in the memory of the controller hardware.

V. SIMULATION RESULTS

The DSTATCOM is coupled to the power system in parallel with other loads. There is only reactive power associated with the compensation. Therefore, the dc bus voltage is self-controlled, the switching losses are supplied by the line, and no external dc supply is required.

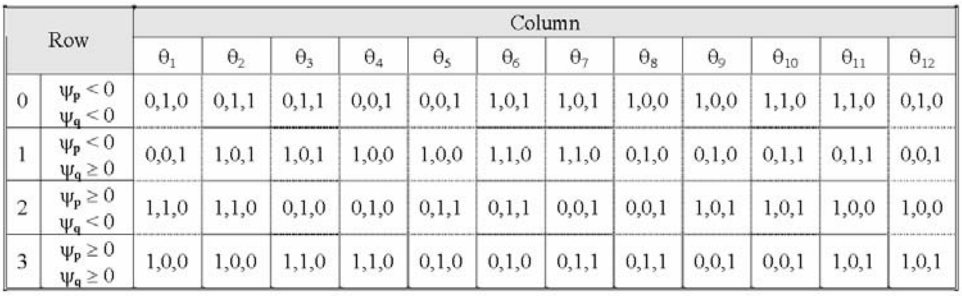
For voltage flicker compensation, the power rating requirement of the compensator is dependent on the line reactance and the load current fluctuation amplitude. With the fluctuation simulated as a harmonic current source modulated with 15 Hz, the simulation results obtained before and after compensation are shown in Fig. 6.

TABLE.I PRINCIPLES FOR SPACE VECTOR SELECTION



Power errors	Criteria for the choosing of voltage space vectors	Application examples (in sector 1)
$\psi_q \geq 0$	Select the voltage vector that forces the converter output current lag in phase.	Choosing V_1 (1,0,0) or V_6 (1,0,1) in the case of $\psi_p \geq 0$.
		Choosing V_7 (1,1,1), V_8 (0,0,0) or V_5 (0,0,1) in the case of $\psi_p < 0$.
$\psi_q < 0$	Select the voltage vector that forces the converter output current lead in phase.	Choosing V_2 (1,1,0) in the case of $\psi_p \geq 0$.
		Choosing V_7 (1,1,1), V_8 (0,0,0), V_3 (0,1,0) or V_4 (0,1,1) in the case of $\psi_p < 0$.
$\psi_p \geq 0$	Select the voltage vector that drives the converter output current increase.	Choosing V_1 (1,0,0) or V_6 (1,0,1) in the case of $\psi_q \geq 0$.
		Choosing V_2 (1,1,0) in the case of $\psi_q < 0$.
$\psi_p < 0$	Select the voltage vector that drives the converter output current decrease.	Choosing V_7 (1,1,1), V_8 (0,0,0) or V_5 (0,0,1) in the case of $\psi_q \geq 0$.
		Choosing V_7 (1,1,1), V_8 (0,0,0), V_3 (0,1,0) or V_4 (0,1,1) in the case of $\psi_q < 0$.

TABLE II OPTIMUM SWITCHING TABLE BASED ON THE INSTANTANEOUS POWER AND VOLTAGE SPACE VECTOR



Row		Column											
		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
0	$\psi_p < 0$ $\psi_q < 0$	0,1,0	0,1,1	0,1,1	0,0,1	0,0,1	1,0,1	1,0,1	1,0,0	1,0,0	1,1,0	1,1,0	0,1,0
1	$\psi_p < 0$ $\psi_q \geq 0$	0,0,1	1,0,1	1,0,1	1,0,0	1,0,0	1,1,0	1,1,0	0,1,0	0,1,0	0,1,1	0,1,1	0,0,1
2	$\psi_p \geq 0$ $\psi_q < 0$	1,1,0	1,1,0	0,1,0	0,1,0	0,1,1	0,1,1	0,0,1	0,0,1	1,0,1	1,0,1	1,0,0	1,0,0
3	$\psi_p \geq 0$ $\psi_q \geq 0$	1,0,0	1,0,0	1,1,0	1,1,0	0,1,0	0,1,0	0,1,1	0,1,1	0,0,1	0,0,1	1,0,1	1,0,1

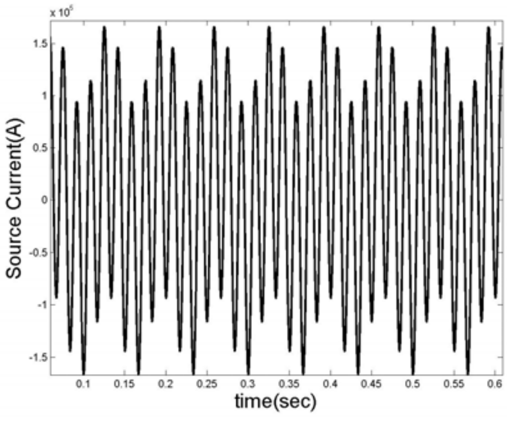


Fig. 6(a) Source current before compensation

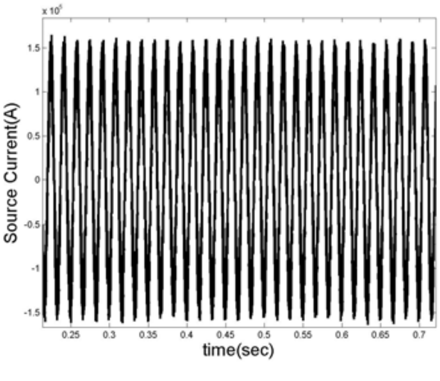


Fig. 6(b) Source current after compensation

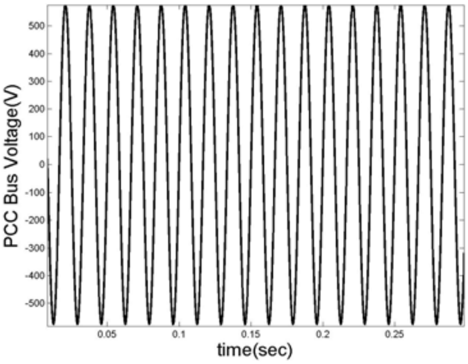


Fig. 6(c) PCC bus voltage before

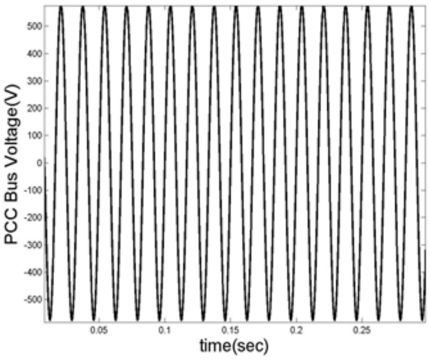


Fig. 6(d) PCC bus voltag after

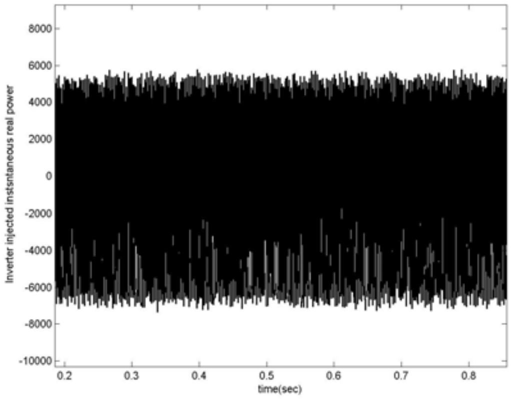


Fig. 6(e) Inverter injected instantaneous real power p

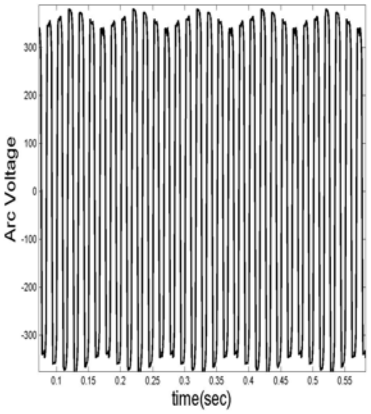


Fig. 6(f) Voltage arc before

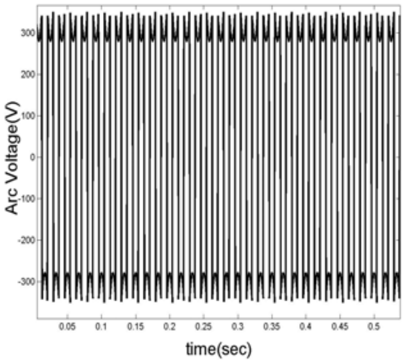


Fig. 6(g) Voltage arc after

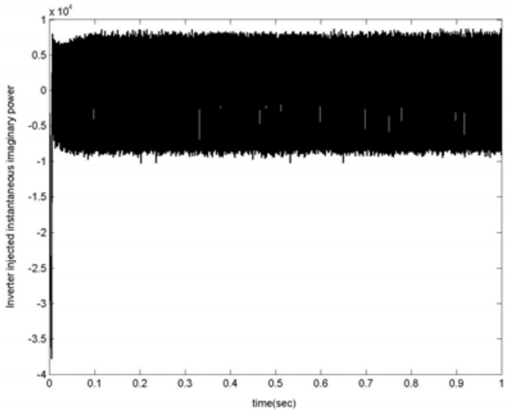


Fig. 6(h) Inverter injected instantaneous imaginary power q

VI. CONCLUSIONS

This paper describes mitigation of voltage flicker and load harmonics using a DSTATCOM. A new control scheme is used and developed, based on direct power control (DPC), where the instantaneous real power and imaginary power are directly controlled. By integrating the dc-bus voltage and ac line current variables into one control loop, the multiple cascaded loop structure is avoided, and fast dynamic response is obtained. The current control bandwidth is larger than that with conventional current controlled DSTATCOMs. In addition, the scheme is suitable for decoupled active and reactive power control (power factor correction).

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GƏRGİNLİYİN TƏNZİMLƏNMƏSİ MƏQSƏDLİ STATİK SİNXRON KOMPENSATOR VASİTƏSİLƏ FƏZA VEKTORUNUN MODULYASİYASI ƏSASINDA ELEKTROENERJİYƏ HİSTEREZİSLİ NƏZARƏT

ŞƏYANFƏR H.A., KƏZEMİ A., KƏRƏMİ M.

Paylayıcı sistemlərdə, elektroenerji təchizatında müvəqqəti qısa fasilələri məhdudlaşdırmaq, gərginliyin azalmasının qarşısını almaq, gərginliyin və tezliyin rəqslərini azaltmaqda və umumiyyətlə elektrik enerjisinin keyfiyyətinin yaxşılaşdırılmasında statik sinxron kompensatorların tətbiqi yüksək effektivliyə malikdir. Təqdim olunan məqalədə inventor üçün fəza vektorunun modulyasiyasına əsaslanan histerezis enerji nəzarətçisi şərh olunmuşdur. Adi sinxron kompensatorlar dəyişən cərəyan və sabit gərginlik dövrələrində ikikaskadlı nəzarətçi kimi tətbiq olunurlar. Üsulun üstün cəhətləri sadəliyindən, etibarlığından və rəqslərə, harmonikalara yaxşı nəzarətindən ibarətdir.

ГИСТЕРЕЗИСНЫЙ КОНТРОЛЛЕР ЭЛЕКТРОЭНЕРГИИ, ОСНОВАННЫЙ НА МОДУЛЯЦИИ ПРОСТРАНСТВЕННОГО ВЕКТОРА С ПОМОЩЬЮ СТАТИЧЕСКОГО СИНХРОННОГО КОМПЕНСАТОРА, С ЦЕЛЬЮ УМЕНЬШЕНИЯ КОЛЕБАНИЙ НАПРЯЖЕНИЯ

ШАЯНФАР Г.А., КАЗЕМИ А., КАРАМИ М.

Статические синхронные компенсаторы являются эффективным способом улучшения качества электроэнергии в распределительных системах, заключающемся в ограничении временных перерывов в электроснабжении, уменьшении снижения напряжения, сглаживании колебаний напряжения и частоты. В данной статье описан гистерезисный контроллер энергии, основанный на модуляции пространственного вектора для инвертора, модулированного по ширине полосы. Обычные синхронные компенсаторы используют двухкаскадный контроль цепей переменного тока и цепей постоянного напряжения. Преимущество метода заключается в простоте и надежности контроля, а также в лучшем слежении за колебаниями нагрузки и/или гармоник.