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Power quality improvement using dynamic compensation of reactive power to control the voltage values

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ABSTRACT

The main purpose of this paper is to improve the power quality in H.V transmission system when line is loaded, by producing solutions to voltage variations problems during load varying. The solution method employs the reactive power control by compensation techniques as the basis of voltage regulation to improve the power quality. Dynamic compensation is used to verify this purpose using FACTS technologies by introducing a circuit model of a SVC with multi level of switching capacitor bank as a source of VARs and one stage of inductor as aVAR absorber. The adopted technique here is to measure of the reactive power demand required to keep the bus voltage at its rated value and then the SVC will compensate the needs of VARs in the system by controlling the firing angle of the thyristors. The ability of VARs generation in the suggested model is four times of VARs absorption.

تحسين جودة القدرة باستخدام التعويض الديناميكي للقدرة الغير فعاله للسيطرة على قيمه الفولتيه

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الخلاصه:

ان الهدف الرئيسي لهذا البحث هو تحسين جودة القدرة في انظمة نقل القدرة ذات الضغط الفائق عندما تكون في حالة الحمل بتقديم حلول لمشكلة تغير الفولتية اثناء تغير الاحمال . ان طريقة الحل المقدمة تستخدم السيطرة على القدرة الغير فعالة من خلال تقنية التعويض كاساس لتنظيم الفولتية من اجل تحسين جودة القدرة.ان التعويض الديناميكي قد استعمل لتحقيق هذا الغرض باستخدام التقنيات المرنة لنقل القدرة الكهربائية للتيار المتناوب وذلك بتقديم موديل لدائرة معوض قدرة غير فعالة من مستويات متعددة للمتسعات المفتاحية كمصدر للقدرة الغير فعالة ومحاثة متغيرة لامتصاصها. ان التقنية المستخدمة هنا هي قياس القدرة الغير فعالة الفعلية المطلوبة للحفاظ على الفولتية ضمن القيمة المحددة المطلوبة وعندها سيقوم المعوض بتعويض حاجة النظام من هذه القدرة من خلال السيطرة على زوايا القدح للثايرستورات المستخدمة.ان قابلية هذه الدائرة لتوليد القدرة الغير فعالة في هذا الموديل تعادل 4 مرات قابليتها على امتصاصها

1- Introduction:

AC power systems are designed to operate at a sinusoidal voltage of a given frequency [typically 50 or 60 hertz (Hz)] and magnitude. Any significant deviation in the waveform magnitude, frequency, or purity is a potential power quality problem [Dugan et al 2004]..

Power quality is a term that means different things to different people. Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment.

A simpler and perhaps more concise definition might state: “Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy” [Sankaran 2002] , also the power quality can be defined as' Any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipment. The standards in the power quality area are devoted to maintaining the supply voltage within certain limit, because the power supply system can only control the quality of the voltage and hence the power according to the engineering terms which defines the power as the rate of energy delivery and is proportional to the product of the voltage and current. The ultimate reason that we are interested in power quality is economic value. There are economic impacts on utilities, their customers, and suppliers of load equipment [Dugan et al 2004]. Since the reactive power affects on line current and bus voltage, as well as power factor and consequently the stability of power transmission, the control of VARS is very important and powerful in electric power system. The reactive power control is necessary to : voltage control (keeping voltage with certain limits) to prevent damage in the electric equipment such as overheating motors and generators , reduce the real power losses , maintain system stability, and improve the power system quality and system reliability. According to this importance of Vars control, many researchers discuss this subject; [Blajszczak G. 2007] describes importance of the reactive power control basing on failures and control problems in polish transmission networks with details.

Under the concept of FACTS which are technologies to increase the flexibility of transmission systems by allowing control of power flow and increasing stability limit of transmission line and increasing power transfer capability [Zhang et al 2006, Tyll 2004]. In IEEE standard FACTs are defined as; power electronic based systems and other static equipments that provide control of one or more A.C transmission system parameters to enhance controllability and increase power transfer capability. One of these devices is the SVC (static Var compensator).

Today, power quality issues are becoming an important performance indicator and receiving much more attention than in past. [Khederzadeh 2003] discuss the effects of Thyristor Controlled Series Capacitor (TCSC) and shunt compensation by static synchronous compensators (STATCOM) in term of power quality and their effects on protective relays behavior. While [Zhang et al 2004] present an optimized shunt hybrid power quality conditioner (SHPQC) for the compensation of harmonic and reactive power using full digital compensating system. Therefore the reactive power control is very important for system reliability and voltage regulation along transmission lines, in other words it improves the power quality on power system.

2- Background of the reactive power (Q)

There are three types of powers in AC system:

1- Apparent power S which is given by

$$S = \sqrt{3} V_L I_L \quad [VA] \text{ -------------- } (1)$$

Where V_L and I_L are the line voltage and current respectively.

2- Active power or real power P which is the real value of the apparent power and is given by

$$P = \sqrt{3} V_L I_L COS \phi \quad [Watt] \text{ --------------- } (2)$$

Where φ is the power factor angle.

3- Reactive power Q which is the imaginary part of the apparent power and is given by

$Q = \sqrt{3} V_L I_L SIN\phi$ [VAR] -------------- (3)

The relationship between scalar voltage difference between two nods and the reactive power flow [Drof 2006]:

$$\Delta V = \frac{RP_2 + XQ_2}{V_2}$$

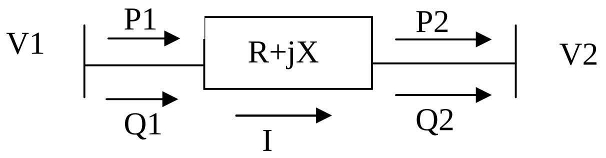

Fig. 2 Reactive power flow between two nods

In most power system X>>R, therefore $\Delta V \propto Q$ i.e voltage difference determines Q.

The reactive power can be either positive or negative depending on the sign of the angle φ as explained by Equation (3).This means that Q can be consumed or can supply energy to the system . A load which has positive Q is said to absorb VARs and it characteristics for inductive loads. While negative Q means reactive power generation and it characteristics for capacitive loads . Therefore in any power system some equipments supply VARs (source of reactive power) which cause to raise the voltage in them like :Capacitors, Over-excited synchronous generators, and lightly loaded transmission lines due to the capacitive charging effect [Casazza 2003] .While another equipment, which absorb VARs (or be a sink of reactive power) lower voltages like: Inductors, transformers, heavily loaded transmission lines, most general customer loads like induction motors & power converters ,under-excited synchronous generators. That means, it is important to balance the supply and load active and reactive power.

However, the voltage plays an important part in maintaining the stability of power transmission. The voltage levels are very sensitive to the flow of reactive power and therefore the control of it is very important. This is the subject of reactive compensation .

3- Compensation techniques in power systems

The basic idea of the power system compensation is "injection of reactive power (VARs) to the system with opposite sign to balance or control system Vars", i.e it will be desired to reduce the remaining Q as possible to reduce energy transmission losses. In addition, this idea is used to achieve desired effects in the electric power. The effects include improved voltage profiles, enhanced stability performance and improved transmission capacity and power quality.

There are four main objectives for the use of compensation devices:

1-Voltage regulation. **2**-Load balancing.

3-Power factor correction. **4**-Harmonic filtering.

Each of them represents important part of power quality as defined early, therefore the power quality can be improved by using this technique.

Generally, there are two categories of power system compensation, static compensation and dynamic compensation. Static compensation uses fixed reactive components such as capacitor banks and reactors. Dynamic compensations are considered as dynamic reactive power devices capable of changing (or controlling) their output according to system voltage. The main objectives of dynamic VAR compensation are to increase the stability limit of the a.c power system to decrease terminal voltage fluctuation during load variation. It includes synchronous generators, synchronous condensers, flexible AC transmission system which are including static var compensators (SVC), static compensators (STATCOM) and dynamic VAR (D-VAR)[Zhang et al 2006]. This paper introduces a circuit model of SVC for voltage regulations to improve the quality of power according to the performance of this compensator.

4-Static VAR compensation

SVC are essentially thyristor-controlled reactive power devices (capacitors and inductors) for providing fast – acting reactive power compensation on H.V transmission network and can be applied to either utility systems or industrial systems [Benysek G.2007, Zhang et al 2006, Dugan R.2004]. The dynamic nature of SVC lies in the use of thyristors in the switching of capacitors or inductors to get very fast and fine control of system voltage. There are two basic arrangements of the thyristor controlled reactive power devices:

4.1- Thyristor controlled reactor (TCR)

The TCR is defined in IEEE terms as "shunt connected thyristor controlled inductor whose effective reactance is varied in continuous manner by partial conduction control of the thyristor valve". In other words, the fundamental frequency current component through the reactor is controlled by delaying the closing of the thyristor switch with respect to the natural zero crossing of the current [Chen 2004]. This means that the current in thyristor can be continuously varied from zero to maximum by phase angle controlling the gate signal to the thyristors. Fig.3 shows the basic arrangement of the TCR and its waveforms.

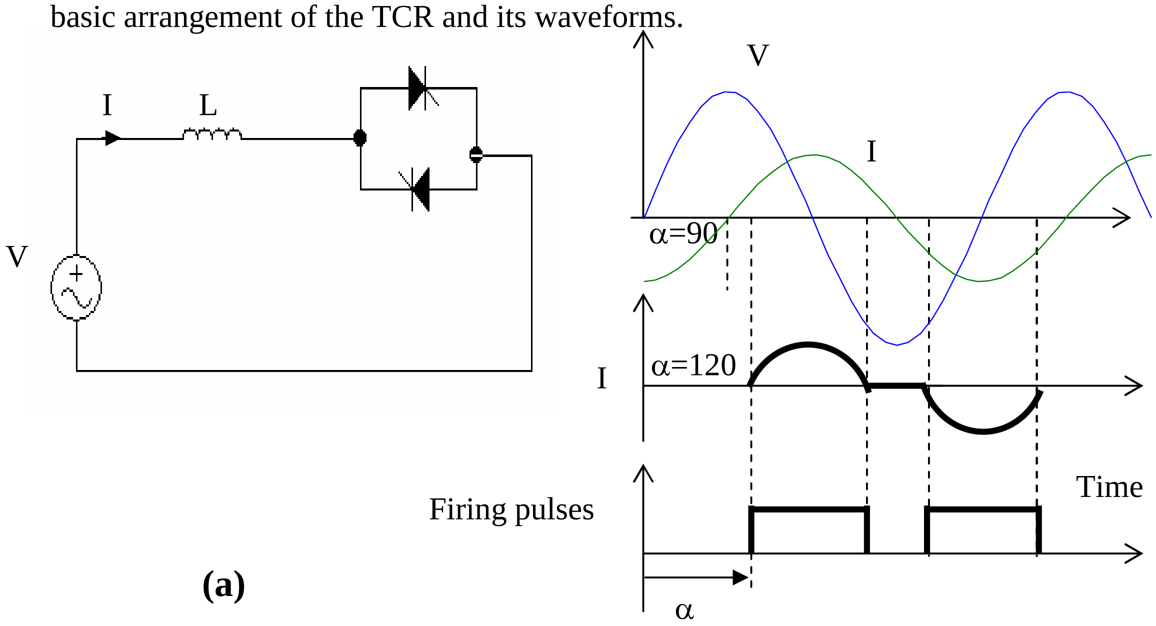

Fig. 3 (a) The TCR arrangement **(b)** its waveforms.

It is clear that α is governing the inductor current. When $\alpha = 90^o$, then the inductor current will be sinusoidal. When $\alpha = 180^o$,then the inductor current will be zero. Hence, the inductor current is controlled within the range of $90^o \le \alpha \le 180^o$. Fig.3b shows the case at which $\alpha = 120^o$. It is obvious that the inductor current is not sinusoidal but it contains fundamental and harmonic currents. The chopped current contains all odd harmonics order 3, 5, 7, etc.

4.2- Thyristor switched shunt capacitor (TSC)

As shown in fig (4), the basic circuit of TSC consist of a capacitor connected in series with two opposite thyristors, so that one operates (conducts) in positive half cycle of the supply , while the other conducts in the negative half cycle .

It offers stepwise control, and it produces switching transient which is considered as a one of the disadvantages of this circuit. Since the TSC allows current to flow when thyristors are ON (gated) and prevents flowing of current when thyristors are off (blocked), the transient will occur when the TSC is switched off while the current through it is not zero. To get transient free switching, the voltage across a capacitor must either at its positive or negative peak to make the current the capacitor current start from zero [Tyll 2006].

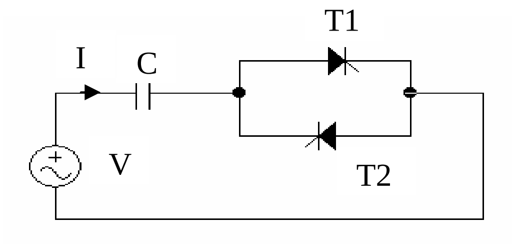

Fig.4 The basic circuit of TSC

The relationship between the compensator current and the number of conducting capacitors at constant terminal voltage is shown in Fig .5 [Acha 2002].

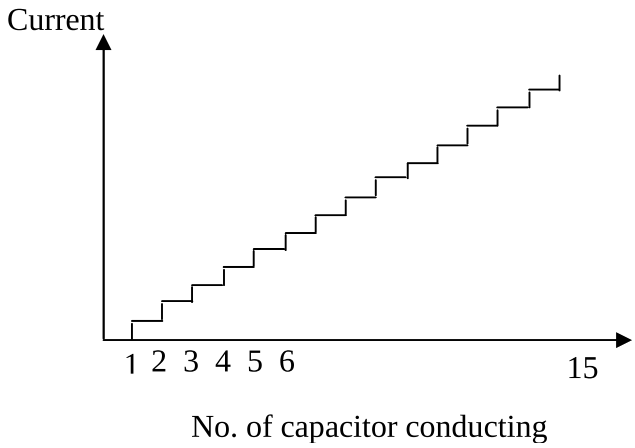

Fig. 5 Relationship between current and No. of conducting capacitors in the TSC.

In general the bus voltage is rather tending to be below their rated values and this is because of the nature of the power system network which is always characterized by inductive loads. Therefore, we have presented a static VAR compensator for bus voltage control purposes.

5- The proposed system schematic design

In the practical network, the bus voltage is usually tending to be less than its rated value because of heavily inductive load. Hence, generation of reactive power is necessary here for treating the reduction in bus voltage. Sometimes, the bus voltage grows above its rated value and this is due to capacitive impedances appearing during light loads. In this case, absorption of reactive power is needed in order to treat the excess in the bus voltage. According to above, we have proposed a system, which has a capability of generation of reactive power equal to four times it capability of absorption. Fig.6. shows the single-phase representation of our proposed reactive power compensator. Here, the step-down transformer lowers the bus voltage to nVbus where n is the step down turn-ratio and Vbus is the r.m.s value of bus voltage.

Assume that the total capacitance required for the switched capacitor bank is C_T then, the maximum r.m.s value of VAR that can be generated is $n^2V_{bus}{}^2\omega C_T$ and the maximum r.m.s value of VAR that can be absorbed is $(n^2V_{bus}/\pi\omega L)(2\pi-2\alpha+\sin 2\alpha)$, where L is the inductance of the TCR and α is its firing angle. The fundamental current amplitude of the TCR is$(nV_{bus}/\pi\omega L)\ )(2\pi-2\alpha+\sin 2\alpha)$, while the maximum r.m.s capacitive current is $nV_{bus}\omega C_T$. Now if the capacitance C_T is divided into 15 equal capacitances and each one of them is equal to C, then C_T will equal to 15C. C_T is distributed on four capacitors C_1, C_2, C_3 and C_4 and their capacitances are C, 2C, 4C and 8C respectively. This distribution allows for the step capacitance control in range of 0 to 15 steps as shown Fig .5

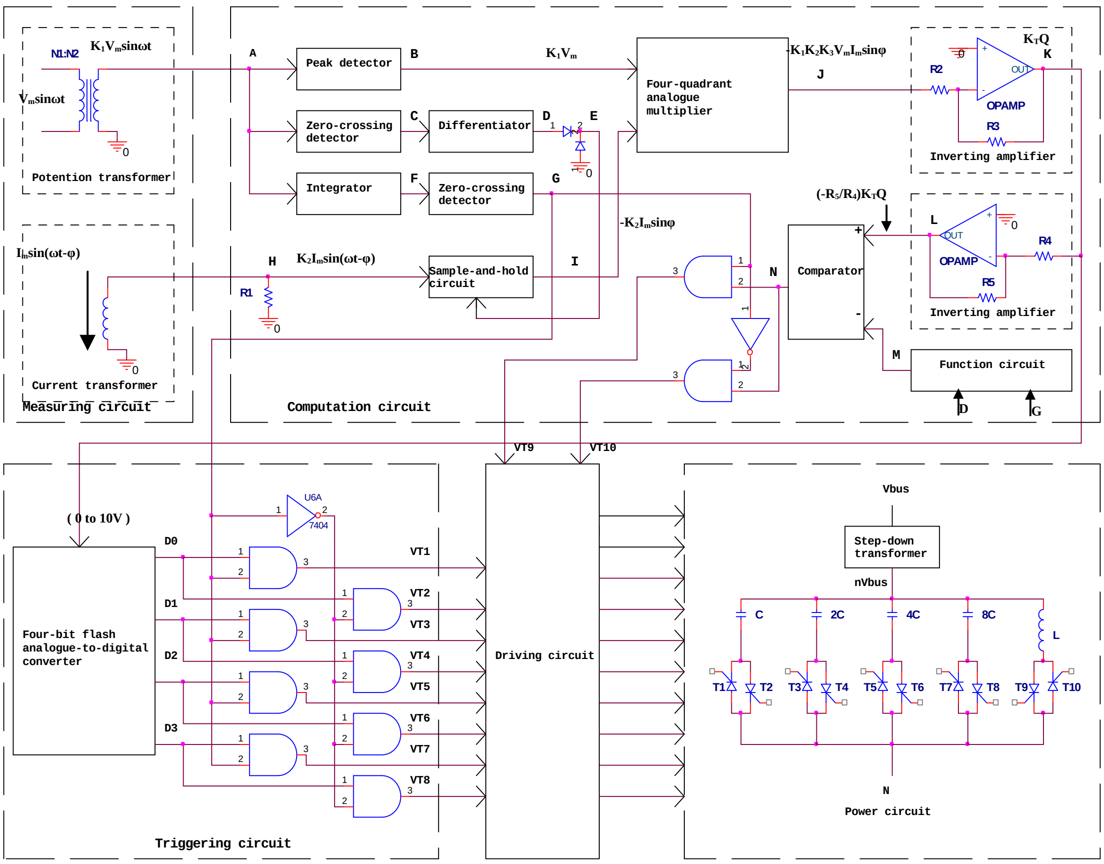

Fig.6 The schematic diagram of 1- phase SVC for voltage control purposes.

The nth harmonic of TCR current is given by

$$a_n = \frac{4nV_m}{\omega L\pi}\left[\frac{\sin(n+1)\alpha}{2(n+1)} + \frac{\sin(n-1)\alpha}{2(n-1)} - \frac{\cos\alpha \sin n\alpha}{n}\right]$$

Where V_m is the bus voltage amplitude.

The control process is achieved by using 4-bit flash ADC for triggering the switching devices of the switched capacitor bank.

6- System performance

The instantaneous value of the bus voltage (V_{bus} = Vm sin ωt) is detected by the potential transformer included in the measuring circuit. The output of this transformer is ($K_1V_m\sin\omega t$). Here K_1 represents the turn ratio N_2/N_1 of the potential transformer. The current transformer detects the load current ($i_L= I_m\sin(\omega t-\varphi)$). Where φ is the power factor angle of the load current. The output of this transformer is $K_2I_m\sin(\omega t-\varphi)$ and K_2 is determined by the number of turns of the of the secondary winding of the current transformer and the resistance R_1.The AC voltage at point A is peak-detected to yield the DC voltage K_1V_m appearing at point B as the first input of four–quadrant analogue multiplier. Also the AC voltage at point A is exerted on a zero-crossing detector, so that a rectangular waveform of amplitude of 5 V is generated at point C. This waveform is differentiated and then unified such that a train of positive pulses oriented at (ωt = 0, 2π, 4π,…) is produced at point E. These positive pulses are used to sample and hold the load current at (ωt = 0, 2π, 4π,…). The output of the sample and hold circuit is a DC voltage equal to $-K_2I_m\sin\varphi$ and represents the second input of the analogue multiplier. The analogue multiplier output is $-K_1K_2K_3V_mI_m\sin\varphi$. Where K_3 represents the analogue multiplier constant. When the load current is lagging behind the bus voltage, then the phase angle φ is positive and the output of the analogue multiplier at point J is a negative DC voltage. For leading load current V_J will be positive. V_J is amplified by an inverting amplifier to yield the DC voltage V_k which is equal to K_TQ, where $K_T= (R_3/R_2)\, K_1K_2K_3$ and $Q=(V_mI_m\sin\varphi)/2$. Here Q represents the r.m.s value of the reactive that must be produced by the compensator such that the bus voltage will be set at its rated value. Note that at the beginning of the compensation process, the bus voltage amplitude V_m is less than its rated value and Q will be less than required, but after few cycles of the bus voltage waveform, Q status will be settled and its value then will be almost equal to the reactive power demand. The quantities K_1, K_2, K_3 and R_3/R_2 are chosen such that the value of V_k corresponding the maximum reactive power demand Q_{max} is 10V. This choice is compatible with four–bit flash analogue–to-digital converter which is characterized by table (1). AS seen in the table, a zero value of Vk corresponds to $D_0=D_1=D_2=D_3=$ logic zero and 10 V value of V_k corresponds to $D_0=D_1=D_2=D_3=$ logic 1. Fig.7 shows the voltage waveforms of the computation circuit.

The triggering signals of the thyristors of the capacitors are generated in the triggering circuit. Thyristor T1, T3, T5, and T7 are triggered at ωt = π/2, 5π/2, 9π/2, etc, while T2, T4, T6, and T8 are triggered at ωt=3π/2, 7π/2, 11 π/2, etc. Fig.8 shows the waveforms of the triggering circuit for the case at which the reactive power required to be generated is Q_{max}. It is clearly indicated that all thyristors are triggered at the proper instants where dv/dt =0. This insures that every capacitor current will start from zero and then grows sinusoidally.

The driving circuit includes ten separate sub-circuits and each one corresponds to an individual thyristor. When Q_{max} is detected then all the capacitors will be switch on to the power system and hence a reactive power of a value of $15\omega Cn_2V_{bus}^2$ will be generated to satisfy the load requirement of the reactive power which is equal to Q_{max}. Assume that the detected Q is 1/2 Q_{max}, then the capacitor of a value of 8C will be switched on and the generated reactive power will (8/15) Q_{max}. The maximum error in the reactive power here is

$$\%error = \frac{\frac{8}{15}Q\max - \frac{1}{2}Q\max}{\frac{1}{2}Q\max} \times 100 \approx 6.6\%$$

The maximum error that may associate the reactive power generation is restricted with ±6.6 %. This error has almost negligible effect on the bus voltage status.

Table(1) The characteristic of 4-bit flash analogue to digital converter

V_{in} (Volt)	D0	D1	D2	D3
0	0	0	0	0
(10/15)	1	0	0	0
2 (10/15)	0	1	0	0
3 (10/15)	1	1	0	0
4 (10/15)	0	0	1	0
5 (10/15)	1	0	1	0
6 (10/15)	0	1	1	0
7(10/15)	1	1	1	0
8(10/15)	0	0	0	1
9(10/15)	1	0	0	1
10(10/15)	0	1	0	1
11(10/15)	1	1	0	1
12(10/15)	0	0	1	1
13(10/15)	1	0	1	1
14(10/15)	0	1	1	1
10	1	1	1	1

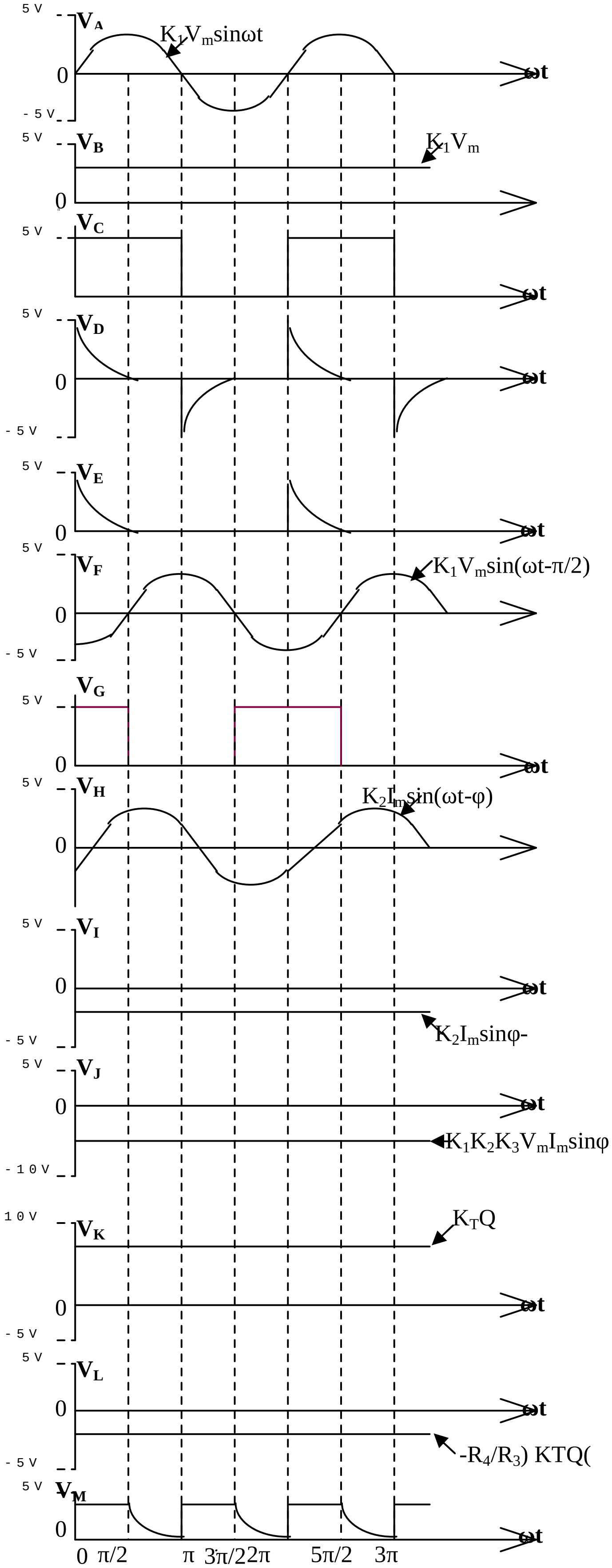

Fig.7 The voltage waveform of computation circuit.

When the load current is leading the bus voltage then, φ will be negative and hence V_J will be negative too. V_K in this case has no effect on the flash analogue-to-digital converter, but V_L will be positive. The positive value of V_L will be compared with a waveform at M in order to determine the angle α required to make the TCR absorb a reactive power equal to$(n^2V_{bus}^2/\pi\omega L)(2\pi\text{-}2\alpha\text{-}\sin 2\alpha)$

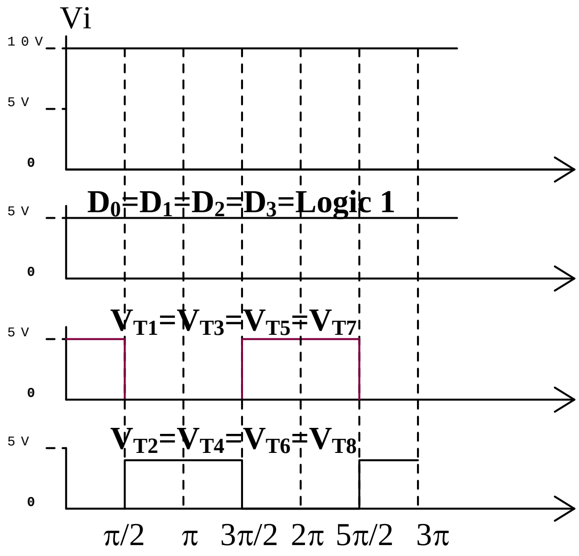

Fig.8 The capacitor triggering circuit waveforms for the case at which $Q = Q_{max}$.

which is equivalent to $-R_5/R_4K_TQ$. Since we have chosen that the maximum VAR absorbed equal to 0.25 the maximum VAR generated, then R_5/R_4 must equal to 0.25. The waveform at point M is generated by using analogue devices. The quantity $(2\pi\text{-}2\alpha\text{-}\sin 2\alpha)$ will be written in the form $(\pi\text{-}2\alpha'\text{-}\sin 2\alpha')$ by the substitution of α in terms of α'. Since the maximum expected value of DC voltage V_K is 2.5V, then the expression $(\pi\text{-}2\alpha'\text{-}\sin 2\alpha')$ must be multiplied by $2.5/\pi$ in order to be compatible with V_L as stated in Fig.9 This figure shows the firing signals of T_9 and T_{10}. When V_L is negative, then the output of the comparator at point N will be zero and the TCR is not enabled.

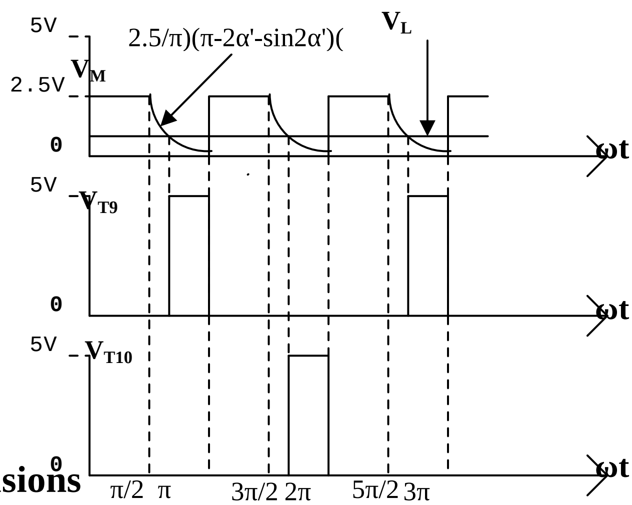

Fig.9 The TCR triggering circuit for a leading load current.

7-Conclusions

In today's competitive energy markets, power quality issues are becoming an important subject in power plants and receiving much more attention than in past. The main purpose of this work is to present a circuit model to improve the power quality by regulating (controlling) the voltage in H.V transmission system, which is generally varied according to the line loading status . By using reactive power compensation techniques including switched capacitor bank and variable inductor together for achieving the control process. The combination of these techniques offers fast and reliable control to the bus voltage which is identified by the following:

1- The capability of generation maximum VAR is four times the capability of maximum VAR absorption.
2- The VAR generation is achieved in 15 steps .
3- The VAR absorption is continuously accomplished by a variable inductor.

In our work single phase model is presented. The three-phase presentation is simply achieved by varying the control circuit and the power circuit. The power circuit for the compensator for three-phase application is wye or delta connected for both TCR and TSC. The control circuit is achieved by varying the triggering circuit such that it will be capable for triggering all the switching devices.

References:

Acha E., Agelidis V.G., Anaya_Lara O., Miller T.J.E. (2002) Power electronic control in electrical system. Newnes press, pp438.

Benysek G. (2007) Improvement in the quality of delivery electrical energy using power electronics systems. Springer press, pp155.

Blajszczak G. (2007) Reactive power control in transmission network as a tool for reliable supply, 9th International conference on electrical power quality and utilization ,Barcelona, 9-11 October, pp4.

Casazza J., Delea F. (2003) Understanding electric power systems. IEEE press, Wiley Intersince , pp231.

Drof R. (2006) Electrical engineering handbook, systems, controls, embedded, energy , machines. Taylor and Francis press, pp672.

Dugan R., Mc Granaghan M. , Santoso S. , Beaty H. (2004) Electrical power system quality . MC Graw- Hill, pp525.

Khederzadeh M. (2003) Power quality impacts of series and shunt compensated lines on digital protective relays, International conference on power systems transients ,IPST ,New Orleans , USA,pp.6.

Sankaran C. (2002), power quality. CRC press pp.202.

Tyll H. (2004) Facts technology for reactive power compensation and system control. IEEE/ PES, transmission and distribution conference& Exposition, Sao Paulo.

Tyll H. (2006) Application of SVCs to satisfy reactive power needs of power systems. IEEE/ PES conference in transmission and distribution , p. 487-492.

Thukaram D., Jenkins L. , Visakha K. (2006) Optimum allocation of reactive power for voltage stability improvement in AC-DC power system. IEE proceedings Generation, transmission and distribution ,153: p 237-246.

Zhang M. Sun H. , Zou J (2004) An optimized shunt hybrid power quality conditioner for harmonic and reactive power compensation in distribution networks , International conference on power system technology , Singapore,November, pp.6.

Zhang Xiao – Ping, Rehtanz C., Pal B. (2006) Flexible AC transmission system : modeling and control . Springer press, pp380.