Impact of static reactive power compensator (SVC) on the power grid

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Abstract: - The work presented in this paper is a contribution to the problem of controlling the reactive powers and the voltages in an electrical network. Among these control tools, the static reactive power compensator (SVC) has been chosen because of its simplicity of control. The SVC is among the FACTS 'Alternative Flexible Current Transmission Systems' devices that help to deal with problems encountered in the operation of electrical networks either in the distribution side or in the transport side. In this work, the SVC is used to control the reactive power and the voltage in an electric power transmission network. In order to improve its efficiency, three voltage regulation systems have been chosen in the control system of this compensator.

1 Introduction

Increasing use of electric energy in the economic, social and industrial life of each country causes more and more problems of disturbance, overvoltage, voltage drop and harmonics in the electrical networks. The rapid development of power electronics has had a considerable effect in improving the operating conditions of power grids by performing control of their parameters by introducing control devices based on very high power electronics components. advanced known as FACTS: Alternative Current Transmission Systems. The research reported in this paper is motivated by the desire to improve the control of reactive powers and voltages in an electric power transmission network by means of a device FACTS, the static compensator of reactive power SVC "Static Var Compensator" .

The SVC static compensator based on controllable power electronics elements is a device used to maintain steady state and transient voltage within the desired limits. SVC injects or absorbs reactive power into the busbar where it is installed to meet the reactive power demand of the load. It allows flexible and continuous control of the voltage at the busbar.

In this work, SVC is used to control the reactive power and the voltage in an electric power transmission network, by using three voltage control system in the control system of this compensator to improve its performance.

2 Static reactive power compensator (SVC)

The SVC Reactive Power Compensation is a device used to maintain the steady-state and transient voltage within the desired limits. SVC injects reactive power into the bar where it is connected in order to satisfy the reactive power demand of the load, the first example of which was installed in South Africa in 1979 [14]. If the SVC is installed at the midpoint of a distribution line, it is possible to make the voltage at the busbar at the connection point equal to the reference voltage by continuously adjusting the reactive power.

In general, SVC is a combination of Thyristor Controlled Reactor (TCR), TSC (Thyristor Switched Capacitor), fixed capacitor banks FC and harmonic filters. In practice, there are different types of static compensators on the transmission lines.

3 Thyristor controlled reactance (TCR)

The TCR is one of the most important components of an SVC. Although it can be used alone, it is used more often in conjunction with a fixed or switched TSC thyristor capacitor, it provides fast, continuous control of reactive power on the power grid. The Thyristor-Controlled Reactor (TCR) thyristor

controlled reactor has a bidirectional thyristor valve T_1 and T_2 connected in series with a fixed inductance coil L, shown in *fig*. 1. The thyristor controlled reactor allows for more precise control of thyristors. the reactive power because it offers a continuous control of the compensation current.

The thyristors are switched on with a certain ignition angle α and drive alternately over half a period. The ignition angle α varies from 90 ° to 180 °. The conduction angle σ is the angle at which the thyristors conduct. A thyristor starts driving when a trigger signal is sent to it and the voltage at its terminals is positive. He stops driving when the current flowing through it vanishes. The thyristors are lit symmetrically every half-period. The fundamental frequency current is regulated by the phase control of the thyristor valve. In full conduction (α = 90 °), the current is essentially reactive and sinusoidal, and when α = 180 °, one is in null conduction [3].
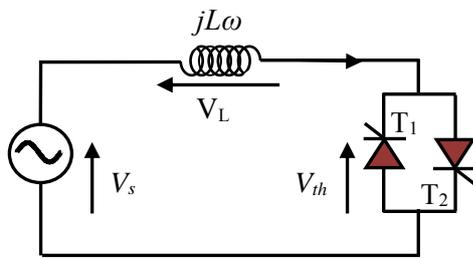

Fig.1. Single-phase circuit of a TCR

Let the source voltage vs given by the following relation:

$$v_s(t) = V_m \sin(\omega t)$$ (01)

Vm: amplitude of the source voltage;
ω: Pulsation of the source voltage.
From Figure.1 the equation of the voltage of the circuit is:

$$L\frac{di_{TCR}(t)}{dt} - v_s(t) = 0$$ (02)

Where L is the inductance of the TCR.
With the initial condition ($\omega t0 = \alpha$), the solution of this equation is given by:

$$i_{TCR}(t) = \frac{1}{L}\int_{\alpha/\omega}^{t} v_s(t)\ dt$$ (03)

We then get:

$$i_{TCR}(t) = -\frac{V_m}{\omega L}\left(\cos\alpha - \cos\omega t\right)$$ (04)

α: is the priming angle in degrees.

According to the Fourier analysis, the fundamental component iTCR (t) of the current is given by the following relation:

$$i_{ITCR}(t) = a_1 \cos\omega t + b_1 \cos\omega t$$ (05)

From equation (04), the current is a function pair iTCR (t) = iTCR (-t), that is to say b1 = 0. The coefficient a1 is given by:

$$a_1(t) = \frac{4\omega}{\pi}\int_{\alpha/\omega}^{\pi/\omega} i_{ITCR}(t).\cos\omega t.dt$$

$$a_1(t) = \frac{4\omega}{\pi}\int_{\alpha/\omega}^{\pi/\omega} -\frac{V_m}{L\omega}(\cos\alpha - \cos\omega t).\cos\omega t.dt$$ (06)

We pose :

$$\cos^2\omega t = \frac{1}{2}(1 + \cos 2\omega t)$$

The magnitude of the fundamental current is the result of equation (06):

$$I_{ITCR}(t) = a_1(t) = \frac{V_m}{\omega L}\left(\frac{2\pi - 2\alpha + \sin 2\alpha}{\pi} \right)$$ (07)

$$I_{ITCR}(t) = V_m B_{TCR}(\alpha)$$ (08)

This relationship can be written as:

$$B_{TCR}(\alpha) = B_{max}\left(\frac{2\pi - 2\alpha + \sin 2\alpha}{\pi} \right)$$ (09)

With:

$$B_{max} = \frac{1}{\omega L} = \frac{1}{X_L}$$

X_L is the reactance of inductance L
The relation between the initiation angle α and the conduction angle σ and given by [1]:

$$\alpha + \frac{\sigma}{2} = \pi$$ (10)

So the relation giving the fundamental of the current becomes:

$$I_{1TCR}(\sigma) = VB_{max}\left(\frac{\sigma - \sin\sigma}{\pi} \right)$$ (11)

Figure 3 shows the relationship between susceptance B_{TCR} and initiation angle α. Thus the TCR acts as a variable susceptance. It is observed that the susceptance decreases between its maximum value B_L and zero when the ignition angle α varies from 90 ° to 180 °, as well as the fundamental component of the associated current, which makes it possible to adjust the reactive power to be absorbed by the reactance.
The TCR is also called reactive power compensator, it is a continually adjustable reactance. The TCR is the simplest type of SVC.
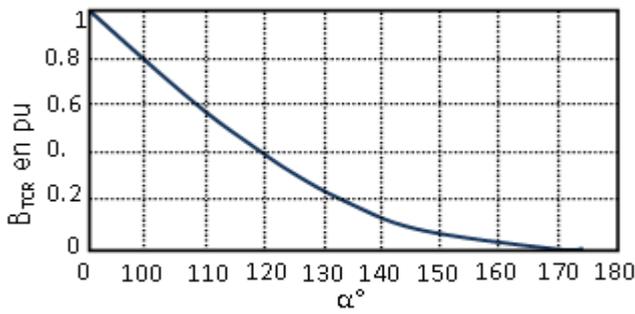
Fig. 3. Characteristic of susceptance

B_{TCR} depending on the α initiation angle
We can write also:

$$I_{1TCR}(\sigma) = V B_{TCR}(\sigma) \qquad (12)$$

With:

$$B_{TCR}(\sigma) = B_{max}\left(\frac{\sigma - sin\,\sigma}{\pi}\right) \qquad (13)$$

According to *fig 3*, for a value α = 90 ° the susceptance B_{TCR} takes its maximum value B_{max} equal to the unit and the value of α increases, it is found that B_{TCR} decreases to its minimum value Bmin zero.

4 TSC Thyristor Switched Capacitor

In this case, the thyristor-switched capacitor TSC (Thyristor-Switched Capacitor) is composed of a fixed capacitor C plus an attenuation inductance coil L connected in series with a bidirectional thyristor valve (*fig.* 7).
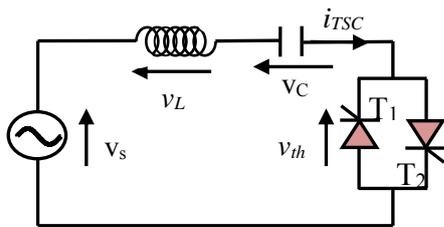

Fig. 7. Single-phase circuit of a TSC with series inductance

The function of the switch is to turn on and off the capacitor for an integer number of half cycles of the applied voltage. The capacitor is thus not controlled in phase, but simply switched on and off. The attenuation inductance serves to limit the current in case of abnormal operation and to avoid resonance with the grating at particular frequencies [2]. To have a minimum of transient disturbances, the switching times are chosen so that the voltage across the thyristors is minimal. Interlocking is therefore performed when the residual voltage of the

capacitor is equal to the instantaneous network voltage.The capacitor can be switched with a minimum of transient if the thyristor is on (state on), at the instant when the voltage v_C of the capacitor and the voltage v_s of the network have the same value. Since the susceptance is fixed, the current in the TSC varies linearly with voltage V (which explains the absence of harmonics on the TSC).

Typically TSC type SVC contains n bench of TSCs mounted in parallel. The susceptance is adjusted by controlling the number of parallel capacitors in conduction. Each capacitor always drives for an integral number of half cycles.

5 Compensator svc constituted by the combination TCR and TSCS

The combination of a TCR (Thyristor Controlled Reactor) and n banks of TSC (Thyristor Switched Capacitor) connected in parallel constitutes the SVC with these great performance of operation (Figure 8). The TSCs used for this mounting of the SVC are connected in series with inductors in order to eliminate the different harmonics of the very high frequencies. The value of the TCR chosen to be 1 / n of the general value of the SVC.
TCR-FC controlled thyristor-capacitor controlled SVC functions as an LC circuit connected in parallel, this can constitute a resonance circuit in AC systems during the course of the energy distribution, can cause serious problems. In this case, a TSC-TCR inserted into the system can act quickly to disconnect all capacitors from the compensator, thus avoiding resonant oscillations.
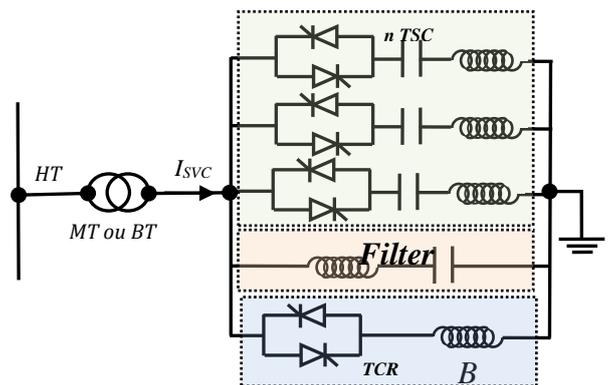

Fig. 8. General structure of an SVC

6 Static characteristic of an SVC [4] [10]
The static compensation of an SVC is obtained according to the behavior of the latter. The static

characteristics of the steady-state control of the SVC are shown in *fig. 9*. The slope [0A] which is the susceptance of the capacitor BC, indicates that the reactive power is supplied by the SVC (capacitive behavior 'Q_{cap} where this power and the current take a negative sign. The slope [BC], which is the susceptance of the inductance B_L, indicates that the SVC absorbs reactive power (inductive behavior 'Q_{ind}'). V_{ref} is the reference voltage at which the SVC does not exchange reactive power with the power grid. In practice, this voltage varies according to a typical margin of ± 10%. The slope of the characteristic reflects a variation of the voltage with the current of the compensator and therefore it can be considered as an X_s reactance of the inclination. Thus, the SVC is responsible for regulating the voltage at the busbar and maintaining the profile of the voltage-current drop of the linear interval with a slope equal to zero. Note that the SVC current is considered positive when the susceptance of the SVC is inductive, negative when it is capacitive, so we have:

$$I_{SVC} = -B_{SVC}V_{SVC} \tag{22}$$

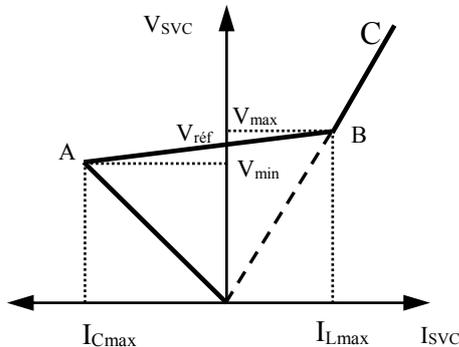$$V_{SVC} = -\frac{I_{SVC}}{B_{SVC}} = -I_{SVC}.X_{SVC} \tag{23}$$

Fig. 9. Characteristic of an SVC

7 SVC command

From an operational point of view, the SVC mimics the operating principle of a variable shunt susceptance controlled by fast thyristors to obtain a fast adjustment and only during some periods of the fundamental frequency. The SVC adjusts these values automatically in response to changes in network operating conditions as it has possibilities to establish capacitive or inductive currents of this network. The operation of an SVC is based on the main function of the essential elements that constitute this compensator such as the measuring circuits, the voltage regulator, the comparators, and the conduction circuits of TCR and TSC.

The control model of an SVC is shown in Figure 18 with a measured voltage regulator.

In this work we will compare three PI regulators, IP and the PI fuzzy.
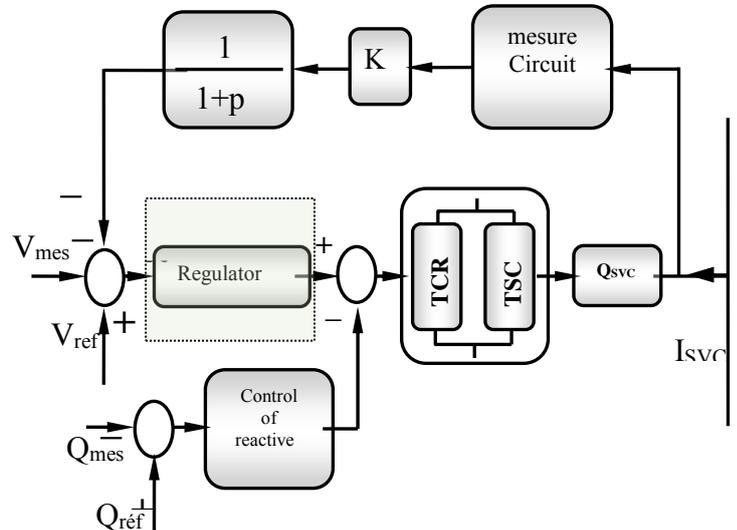

Fig.10. Simplified Block Diagram for Controlling an SVC

The susceptance that results from the voltage regulator is converted into specific information and processed to determine the number of capacitors that must be involved, in order to obtain the α conduction angle necessary to maintain the same control response over the entire range. of SVC operation.

• Susceptibility of SVC as a function of prime angle α:

We have :

$$B_{SVC} = \frac{B_\delta(B_{TSC} + B_{TCR})}{B_\delta + B_{TSC} + B_{TCR}} \tag{33}$$

With **:** $B_{SVCmin} < B_{SVC} < B_{SVCmax}$

B_δ the susceptance of the fixed value transformer;
B_{TSC} takes the values 0 , B_{C1} ,B_{C2} et B_{C3} fixed.
And we have already achieved in the case of the TCR has the following equation:

$$B_{TCR} = \frac{2(\pi - \alpha) + sin 2\alpha}{X_L \pi} \tag{34}$$

With : $X_L = \omega L$

Therefore the B_{SVC} of the static compensator varies as a function of the initiation angle α. The pulsations which control the openings and the closings of the switching thyristors are determined by the different values of the angle α which varies as follows:

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• When the value of $\alpha = 90°$, the TCR leads, this justifies that B_{TCR} becomes B_L.

• When $\alpha = 180°$, the TCR is blocked, its equivalent reactance becomes extremely large ($X_{TCR} >>>$), and so $B_{TCR} = 0$.

All B_{TSC} and B_{TCR} susceptances are used to control voltage (reactive power). If the reactive power of the load is capacitive, the SVC will use the impedance of the TCR equipment to consume the reactive power of the system, by lowering it. Under inductive conditions, TSC capacitors are switched automatically, thus allowing higher system voltage. Therefore, by assembling the TCR which is continuously variable with the angle α, with the TSC, we obtain a power regularly justified in two cases either in advance or late [10].

8 Different voltage regulators

8.1 PI regulator

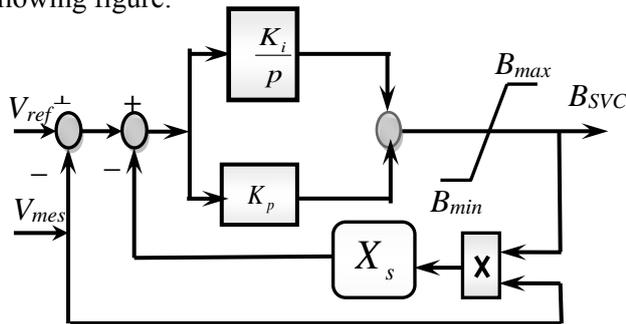The control scheme of the DC voltage by a conventional PI corrector is illustrated by the following figure:

Fig.11. Regulating scheme for the effective value (V_{mes}) of the inter-phase network voltage (PI controller)

Where K_i is a proportional gain, and K_p an integral gain for the PI regulator.

Xs is a reactance (the slope of the characteristic described in the previous chapter) obtained from the following relation:

$V_{mes} = V_{ref} - X_s.I_{SVC}$

8.2 IP regulator

Full IP proportional corrector is essentially different from the PI controller that it has no zero in the transfer function in a closed loop, so its output does not represent any discontinuity in the application of a desired type level [2].

The block diagram of the control voltage V_c including IP correction is illustrated by the following figure:
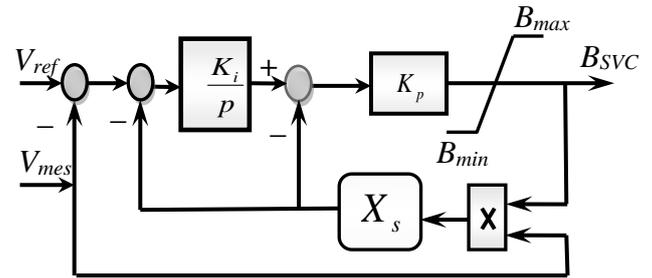

Fig.12. Regulating scheme for the effective value (V_{mes}) of the inter-phase network voltage (IP controller)

8.3 Voltage regulation of the SVC with the fuzzy PI regulator

The conventional PI controller is replaced in the SVC voltage control loop shown in *fig.11*. By the fuzzy PI regulator given in *fig.13*. The basic diagram of the PI-fuzzy regulator rests on the structure of a traditional regulator PI. On found in input and output of the controller fuzzy gains known as "factors of "scale" which allows to change the sensitivity of the fuzzy controller without changing the structure, the input and output variables being normalized.
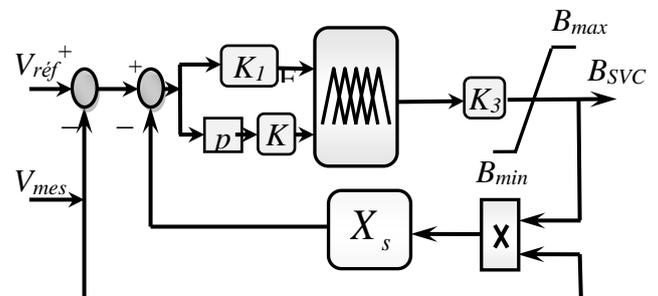

Fig. 13. Regulatory scheme of the rms value (V_{mes}) of the inter-phase network voltage (PI Blur regulator)

We pose:

The error : $E = (V_{ref} - V_{mes}) - X_s.I_{SVC}$

$\dot{E}$: the derivative of the error.

We find in the input and output of the fuzzy controller gains called "scale factors" that can change the sensitivity of the fuzzy controller without changing the structure, the input and output variables being normalized.

Each linguistic variable (E, $\dot{E}$, u) is characterized by seven terms of fuzzy subsets:

NG : negative grand;

NM : negative Medium ;

NP : negative Small;
EZ : about zero;
PG: Positive grand;
PM : Positive Medium;
PP : positive Small.

We have chosen triangular and trapezoidal functions only for input and output variables as shown in *Figures 14, 15* and *16*. They allow an easy implementation and the fuzzification step then requires little computing time during its evaluation in real time. The rule bases in Table 1.
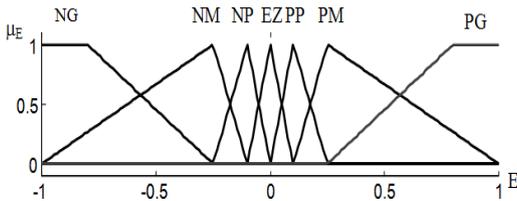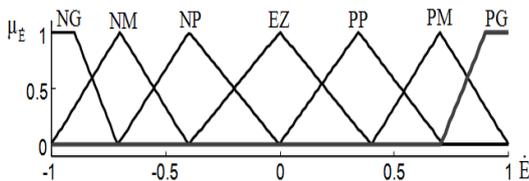

Fig.14. Membership functions of input variable E
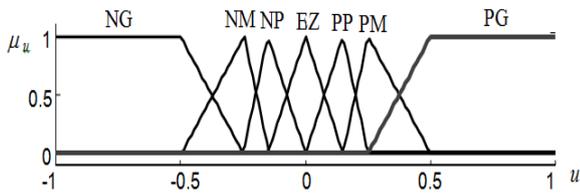

Fig.15. Membership functions of input variable $\dot{E}$

Fig.16.Membership functions of output variable u

Tab. 1.Inference rule of the pi regulator fuzzy managing the output

$\dot{E}$ \ E	NG	NM	NP	EZ	PP	PM	PG
NG	NG	NG	NG	NG	NM	NP	EZ
NM	NG	NG	NG	NM	NP	EZ	PP
NP	NG	NG	NM	NP	EZ	PP	PM
EZ	NG	NM	NP	EZ	PP	PM	PG
PP	NM	NP	EZ	PP	PM	PG	PG
PM	NP	EZ	PP	PM	PG	PG	PG
PG	EZ	PP	PM	PG	PG	PG	PG

The various parts of the SVC studied previously and the electrical network are simulated on the model of SVC on MATLAB-SIMULINK. The structure studied (Fig.11), is composed of SVC with these two parts of power and control, used to compensate

the reactive power and therefore regulates the voltage at the busbar of the power grid, a load connected to the power grid , and finally from a three-phase source with three wires.

To optimize the efficiency of the SVC, we used for the regulation of the effective value (V_{mes}) of the voltage of the network between phase three regulators, the traditional PI, the fuzzy PI and the IP already described. The voltage between phases will undergo different variations thanks to a programmable voltage source. The first variation is an overvoltage at 1.0125 pu, the second is a voltage drop at 0.93 pu (values chosen according to the standards of IEEE and EN) carried out respectively in the intervals of time in seconds [0.1 0.4] and [0.4 0.7]. The SVC compensator controls the fundamental voltage and sends appropriate pulses to the 24 thyristors (6 thyristors for each phase) to obtain the susceptance required by the voltage regulation.
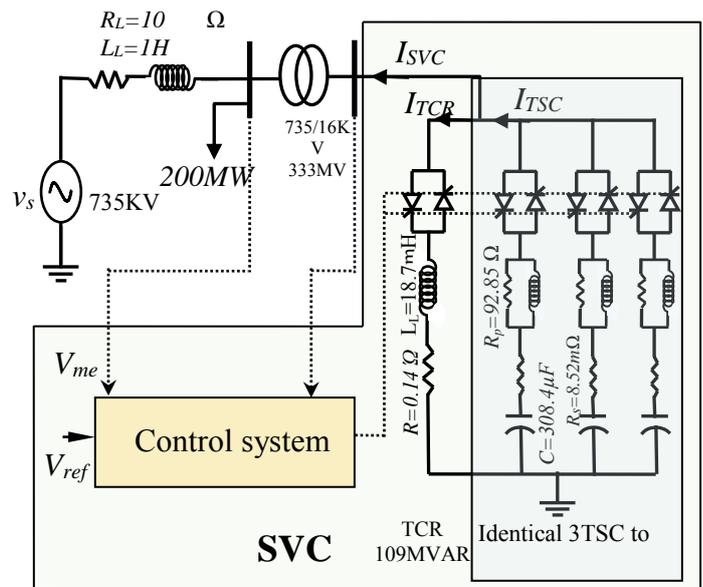

Fig.11. Overall scheme of the system to simulate (single-line diagram)
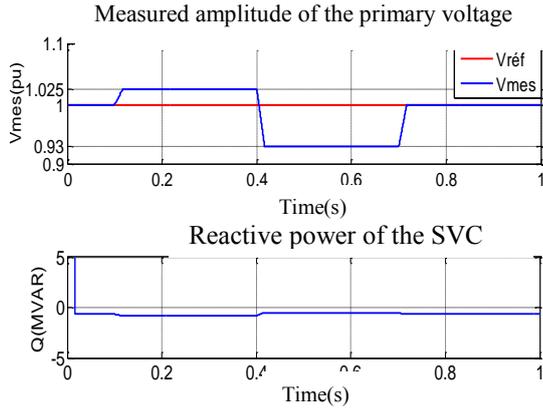
9   Simulation results

9.1 SVC disconnected

Measured amplitude of the primary voltage

Reactive power of the SVC

Fig.14. Simulation results without SVC

9.2 SVC connected

1. Measured amplitude of the primary voltage

Reactive power of the system
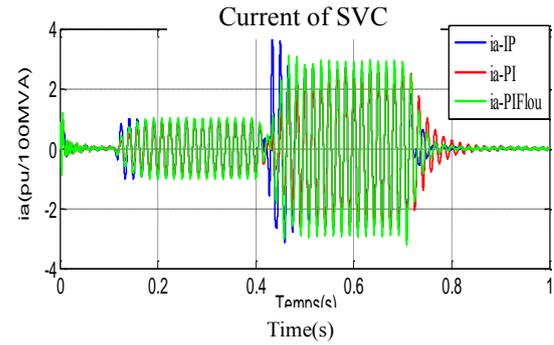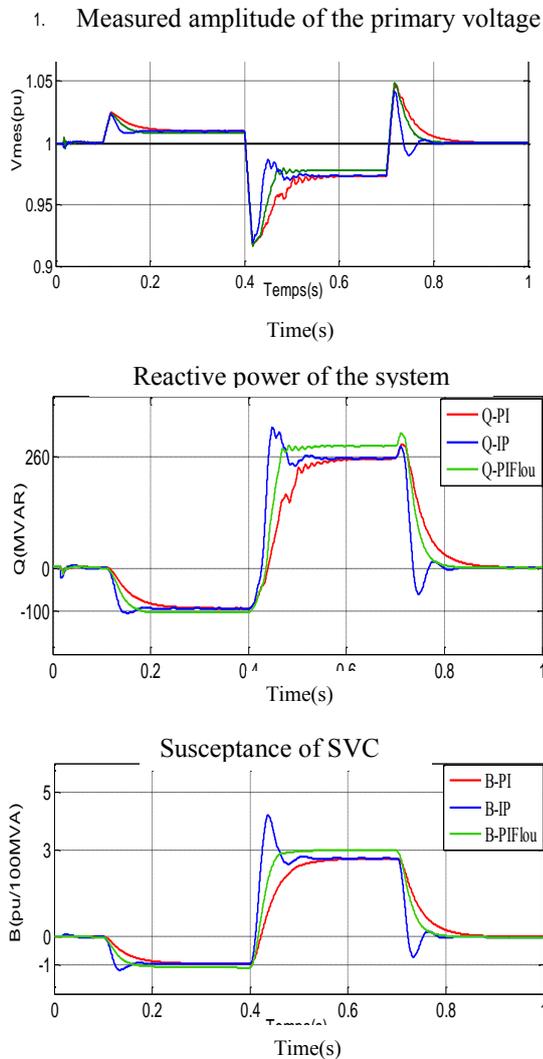
Susceptance of SVC

Current of SVC

Fig.18. Comparative results following the three regulators (SVC connected)

10 Results discussions

Initially the source voltage is set to 1.004 pu. Also the reference voltage V_{ref} is set to 1.0 pu, the SVC is initially floating (zero current). This operating point is obtained with a TSC in operation and the TCR almost in full conduction. At t = 0.1s, the voltage is increased to 1.025pu. SVC reacts for put it back to its reference by absorbing reactive power. At this point all TSCs are out of service and the TCR is almost in full conduction. At t = 0.4s, the source voltage is abruptly decreased to 0.93 pu. SVC reacts by producing reactive power, thereby increasing the voltage near its reference. At this point the three TSCs are in operation and the TCR absorbs approximately 40% of the nominal reactive power. It is observed how the TSCs are sequentially switched on and off. Each time a TSC is initiated, the α angle of the TCR changes abruptly from 180 degrees (no conduction) to 90 degrees (full conduction). Finally, at t = 0.7s, the voltage at the busbar is increased to 1.0 pu and the reactive power of the SVC is decreased to zero.

From Tables 1, 2 and 3 we can say that the SVC with the fuzzy PI regulator gave satisfactory and better results, in fact:

In the time interval of the overvoltage, it can be seen that the SVC was able to improve the voltage and make it up to 1,008 pu by absorbing a reactive power of 103.03 MVAR and reaches almost its minimum value (-109 MVAR) with an angle α = 90 ° (the TCR is in full conduction in this case the TSCs are closed), the susceptance B = -1.09 (pu / 100MVA) also reaches its minimum value -1.04 (pu / 100MVA). From 0.4s to 0.7s the voltage has a drop of 0.07 pu of depth, the SVC with the PI Blur regulator puts this voltage at 0.98 pu by supplying a reactive power of 280 MVAR almost its maximum value (282 MVAR) with an angle α = 135 ° (in this case the three TSCs are in use), the susceptance B =

2.96 (pu / 100MVA) is near its maximum value 3.23 (pu / 100MVA).

Generally the SVC could give satisfactory compensation results using the three voltage regulators. With the fuzzy PI regulator the SVC gave maximum compensation and the results without better compared to PI and IP regulators (figure 18 and 19 and tables 1, 2 and 3). The IP controller has a longer settling time relative to the other two, and has shown slightly better results compared to the PI, parallel to the discussion in the case of the fuzzy PI regulator.

10.1 SVC with the PI controller

Tab. 2. Values of different parameters of the SVC (PI regulator)

Intervals of time (s)	[0 0.1]	[0.1 0.4]	[0.4 0.7]	[0.7 1]
Angle α in degree	95.65°	94.31°	120°	95.50°
Reactive Power (MVAR)	$\simeq 0$	- 92.75	256.00	$\simeq 0$
Tension V_{mes}(pu)	1.00	1.01	0.97	1.00
Susceptance (pu/100MVA)	$\simeq 0$	- 0.95	2.70	$\simeq 0$
Stabilization time (s)	$\simeq 0.00$	0.06	0.1	0.1

10.2 SVC with the IP controller

Tab.3. Values of different parameters of the SVC (IP controller)

Intervals of time (s)	[0 0.1]	[0.1 0.4]	[0.4 0.7]	[0.7 1]
Angle α in degree	94.65°	93.55°	120°	95.00°
Reactive Power (MVAR)	$\simeq 0$	- 93.41	257.00	$\simeq 0$
Tension V_{mes}(pu)	1.00	1.01	0.97	1.00
Susceptance (pu/100MVA)	$\simeq 0$	- 0.95	2.70	$\simeq 0$
Stabilization time (s)	$\simeq 0$	0.03	0.04	0.05

10.3 SVC with the PI fuzzy regulator

Tab.4. Values of different parameters of the SVC (PI fuzzy regulator)

Intervals of time (s)	[0 0.1]	[0.1 0.4]	[0.4 0.7]	[0.7 1]
Angle α in degree	95.55°	90.00°	135°	95.11°
Reactive Power (MVAR)	$\simeq 0$	- 103.03	280.00	$\simeq 0$
Tension V_{mes}(pu)	1.00	1.008	0.98	1.00
Susceptance (pu/100MVA)	$\simeq 0$	- 1.09	2.96	$\simeq 0$
Stabilization time (s)	$\simeq 0$	0.05	0.06	$\simeq 0.06$

11 Conclusions

The variation of the reactive power undesirably contributes to the instability of the voltage in the electrical networks, especially when the generators reach their reactive energy production limits. As a result, appropriate compensation improves and controls the stability of this voltage. The SVC static power compensator is the appropriate FACTS for this purpose because of its high efficiency.

In this paper, we have tried to illustrate the usefulness, efficiency and speed of control of voltages and reactive power by the insertion of the SVC controller. In this challenge we have described existing SVC structure with a detailed study. Simulations are done on the most used model, SVC consisting of a TCR and three TSCs. And to make the latter more efficient we have introduced two voltage regulators in front of the classic PI regulator, the first is the IP and the second is the intelligent controller PI Blur.

The results obtained show that the SVC control device can play a very important role in the field of reactive power compensation and control of the voltages of the different nodes. In particular the SVC with the PI Flou regulator has presented more satisfactory results.

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