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	R (pu)	X (pu)
L1	0.0189	0.0378
L2	0.0170	0.0340

Table (6) Parameters of transformers.

R (pu)	1.25
X (pu)	1.6667
Power factor	0.8
Rated power	1 MVA
Rated voltage	2300 V

Table (7) Parameters for both FLSVC and CSVC schemes.

	FLSVC	CSVC
T_v (s)	0.0	0.0
T_a (s)	0.02	0.02
K_a	20	20
T_i (s)	—	0.08
K_i	—	0.01
B_C (Pu)	0.5	0.5
B_f max (Pu)	1	1
Rated reactive power (Mvar)	10	10

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main terminal busbar.

5-The proposed FLC which can be easily developed in non-linear environment is more robust compared to other supplementary classical controllers (i.e. PID controllers), which require lengthy linearization techniques during the design procedure.

6-The proposed FLSVC is simple to develop and easy to implement.

7-With some slight modifications, the proposed FLSVC can be easily applied, especially to flexible AC transmission systems (FACTS).

Appendix A

This appendix provides the necessary data for the studied sample system.

$\omega_s = \omega_{base} = 377$ rad/s

External network is also considered to be the ideal voltage source (i.e. infinite network), therfore:

$R_g = X_g = B_g = 0$

Table 2 to 7 shows the other necessary data for electrical motors, transmission lines, transformers, static loads and SVCs.

Table (2) Parameters of equivalent asynchronous motor

Stator resistance (Rs)	0.0185 pu
Rotor resistance (Rr)	0.0132 pu
Stator leakage reactance (Xls)	0.085 pu
Rotor leakage reactance (Xlr)	0.085 pu
Magnetizing reactance (Xm)	3.81 pu
Inertia constant (H)	0.5265 s
Rated Power	500 hp
Rated Voltage	2300 V

Appendix B - Nomenclature

v_a , i_a : armature voltage and current for DC motor respectively

T_e , T_L : electrical and load torque for DC motor respectively

v_f : field winding voltage for DC motor

R_f: field winding resistance for DC motor

X_{TCR} : reactance of thyristor controlled reactor

v_t : main terminal busbar voltage

B_f: suceptance of thyristor controlled reactor

τ_a , τ_f: time constant of armature and field winding for DC motor respectively

L_{AF} : mutual inductance between field and armature winding in DC motor

B_c : suceptance of fixed capacitor in SVC

B_g : suceptance of external network

X_g , R_g : reactance and resistance of external network respectively

E_g : voltage of external network

ω_s : synchronous speed

ω_{rsm} : rotor speed of synchronous motor

Table (3) Parameters of equivalent synchronous motor.

Stator resistance (Rs)	0.0121 pu
Rotor field winding resistance (Rfd)	0.0014 pu
d-axis damper winding resistance (Rkd)	0.0302 pu
q-axis damper winding resistance (Rkq)	0.039 pu
Stator leakage reactance (Xls)	0.14 pu
Field winding leakage reactance (Xlfd)	0.267 pu
d-axis damper winding leakage reactance (Xlkd)	0.092 pu
q-axis damper winding leakage reactance (Xlkq)	0.115 pu
d-axis magnetizing reactance (Xmd)	1.03 pu
q-axis magnetizing reactance (Xmq)	0.75 pu
Inertia constant (H)	1 s
Rated power	6000 hp
Rated voltage	2300 V

Table (4) Parameters of equivalent DC motor.

Armature resistance (Ra)	0.0286 pu
Armature leakage inductance (Lla)	0.3150 pu
Field resistance (Rf)	28.6464 pu
Field leakage inductance (Llf)	8099.578 pu
Mutual inductance (Laf)	161.9916 pu
Rated Power	200 hp
Rated Voltage	250 V
Rated speed	600 rpm
Total Inertia (J)	30 Kg. m^2

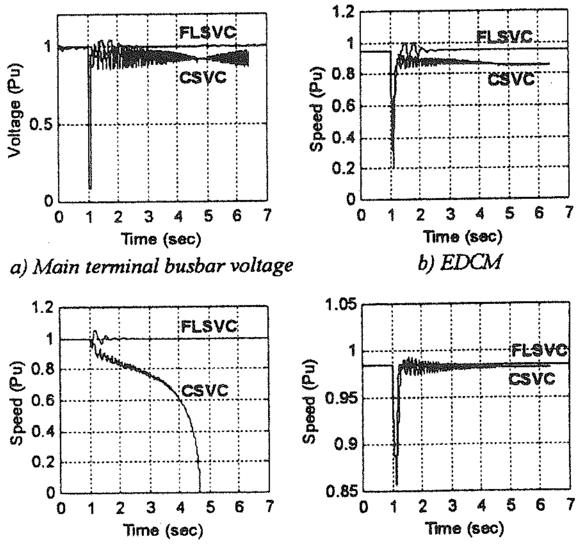
Table (5) Parameters of transmission lines .

	R (pu)	X (pu)	Rated power
T1	0.0019	0.1134	100 MVA
T2	0.0019	0.1134	100 MVA
T5	0.002	0.025	600 KVA
T7	0.004	0.034	20 MVA

- Other transformers assumed to be ideal

5-4-Case 4: Voltage dips analysis

In this case, the effects of voltage dips in the remote external network will be examined. Suppose that the whole system components are operating in the steady state conditions. Let the momentary voltage dips to be occurred in the remote external network at t=1s (E_g=0.4pu) and recovered to its nominal value(E_g=1pu) after 20 cycles. Fig. 13 shows the voltage profile of the main terminal busbar(V_t) and speed variations of all equivalent motors,for both SVC schemes in this case. It is obvious that the FLSVC settles the voltage to 1 pu, whereas the CSVC causes voltagefluctuations (i.e. voltage instability). It is clear that the CSVC is unable to save the synchronous, asynchronous and DC motors (i.e. transient unstable).



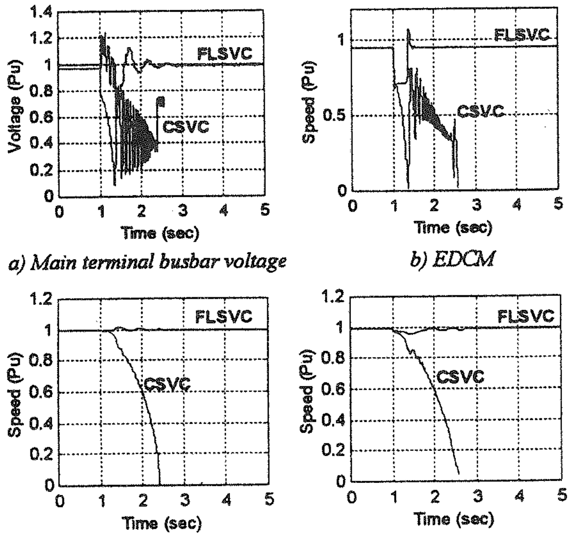
a) Main terminal busbar voltage   b) EDCM

c) ESM   d) ESCAM

Figure (12) Fault analysis.

6-Conclusion

This paper presents a FLSVC applied to an industrial power system. The following issues have been addressed: (1) complete representation of non-linear characteristics of the given power network; (2) appropriate selection of membership functions and rule set based on the proposed fuzzy logic controller capabilities development by non-linear time-domain digital simulations under various operating conditions and disturbances.



a) Main terminal busbar voltage   b) EDCM

c) ESM   d) ESCAM

Figure (13) Voltage dips analysis.

The main achievements are:

1-The proposed FLSVC improves the voltage profile and overall dynamic and transient performance for the given plant compared to the conventional SVC.

2-The non-linear characteristics of the system as well as different operating point can be easily incorporated into the controller development by suitable selection of membership functions and rule set.

3-The proposed FLC which has remarkable effects on the transient and dynamic performance of the given plant has been established by considering only two inputs: $\Delta\omega_{rsm}$ and $\Delta\dot{\omega}_{rsm}$, and one output (U_s). This controller represents a simple non-linear adaptive controller.

4 - similar to our previous report [22] also find out that the proposed FLSVC scheme eventually injects less reactive power to

of the main terminal busbar(V_t) and the speed variations of all equivalent motors, for both SVC schemes. It is clear that the voltage drops to 0.75 pu immediately after simultaneous starting. As observed the FLSVC remarkably settles he voltage to 1 pu, but the CSVC eventually provides 3.5% voltage drop in main terminal busbar. It can be seen that for both schemes, the speed variation of all motors are roughly similar.

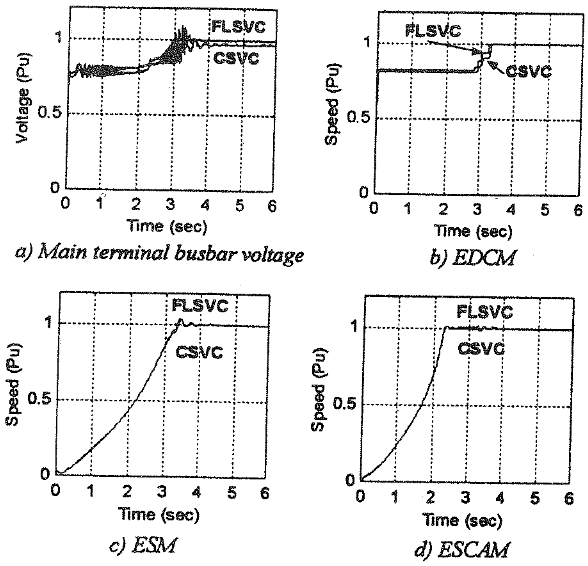


Figure (10) Run - up test.

5-2-Case 2: Sudden Loading Test

Suppose that all no-load motors are completely started and the whole system components are operating in steady start conditions. Let a sudden loading test is then performed at t=1s. The load torque for each motor assumed to be 1 pu based on its own rating. Fig. 11 shows the voltage profile of the main terminal busbar(V_t) and the speed variations of all equivalent motors, for both SVC schemes. For this case, we also observe that the proposed FLSVC works well and settles the voltage to 1 pu and has the better damping performance.

5-3-Case 3: Fault Analysis

In this case, the effects of voltage dips caused by a three phase fault within the industrial network will be evaluated. Suppose that the sudden loading test is completely accomplished and the whole system components are operating in the steady state conditions. Let the three phase fault occurs at point F (Fig. 1) at t=1s and cleared at t=1.1333s (i.e. circuit breakers labeled by B2 and B4 are opened after eight cycles). Fig. 12 shows the voltage profile of the main terminal busbar (Vt) and the speed variation of the equivalent motors, for both SVC schemes in fault analysis case. It is also worthwhile to observe the high performance of the FLSVC in this case. As seen in Fig. 12, the main terminal busbar voltage settles at 1 pu, whereas the CSVC causes voltage fluctuations (i.e. voltage instability). It can be seen that the synchronous motors become unstable due to functionality of CSVC scheme. It is also clear that the CSVC causes puisating vibrations on asynchronous and DC motors shaft after fault clearance.

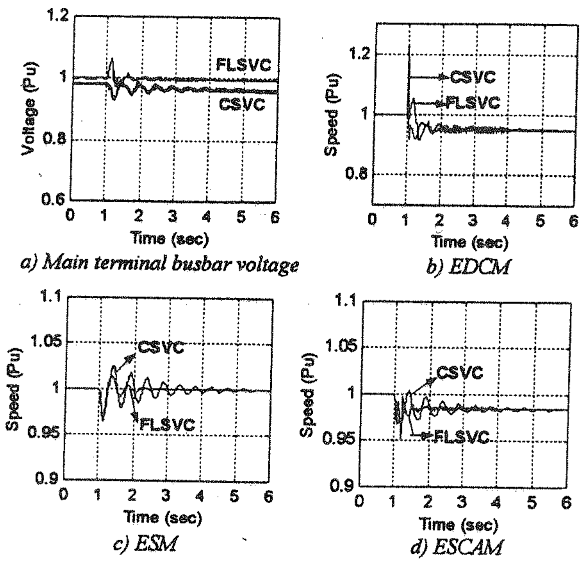


Figure (11) Sudden loading test.

be 20, 0.01 and 0.1 repectively. These optimum values are obtained through repetitive simulations and trial and error procedures in our sample power network.

A fuzzy rule set is then used to describe the FLSVC behaviour as shown in Table 1.Each entry in this table represents a rule of the from 'if accident then consequence', e.g.

if $\Delta\omega_{rsm}$ is NS and $\Delta\dot{\omega}_{rsm}$ is NB then U_s is NB.

The entities of Table 1 could be derived due to expert kowledge. Here, these rules are obtained through a deep investigation into physical aspects of the sample system and digital simulation results belonging to the given industrial plant without consideration of any SVC scheme.

Using the correlation product inference and the center of gravity defuzzification method, the appropriate crisp control signal is then generated [27,33].

Table (1) A sample set of 5*5 rules.

$\Delta\omega_{rsm}$ \ $\Delta\dot{\omega}_{rsm}$	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	NS
NS	NB	NB	NS	NS	NS
ZE	NB	NS	ZE	PS	PB
PS	PS	PS	PS	PB	PB
PB	PS	PS	PB	PB	PB

NB: Negative Big, NS: Negative Small, ZE: Zero, PS: Positive Small, PB: Positive Big

Fig. 9 shows a three dimensional view of the interrelations between the crisp valuse of output signal, and the FLC inputs which graphically represents the nonlinear performance of the proposed FLC.

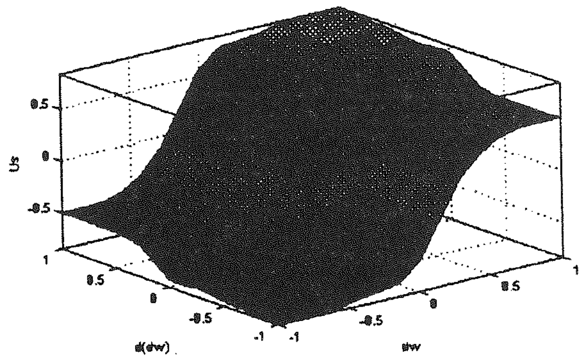


Figure (9)Three dimensional plot of interrelations between the FLC inputs and output.

5-Simulation Studies

In this section, various comparative digital simulation tests are demonstrated for the sample system given in Fig. 1. To show the capabilities and effectiveness of the proposed FLSVC, the results are compared with performance of the CSVC. The main parts of studied sample system including electrical motors, AC/DC drive, transmission lines, power transformers, external network, and static loads are simulation by POWER LAB software, however, the SIMULINK and MATLAB FUZZY LOGIC TOOLBOX linked to above software hsve been used for simulation of both SVC schemes. In the following cases, the value of voltage source in the remote external network (E_g) is set to1pu, unless otherwise stated. The system data are given in appendix A.

5-1-Case 1: Run-up Test

In this case, it is assumed that the no load ESCAM, ESM and EDCM are started at t=0. The ESM is treated as an asynchronous motor during the starting period and the field voltage applied when the rotor speed has been reached 90% of the synchronous speed. It is further assumed that at same time, the equivalent static load (ESL) is connected to its supply transformer. Fig. 10 shows the voltage profile the FLC inputs. Note that

$$\Delta\omega_{rsm} = \omega_s - \omega_{rsm} \quad (1)$$

ω_{rsm} can be easily detected by conventional sensors (i.e. tachometers) and/or sensorless schemes [28-32]. Due to fuzzy logic properties, the estimated values of the speed variations are sufficient in the present study for our purposes and we are actually using the measured noisy data. Thus, our proposed FLC rejects the noise effects. Therefore, $\Delta\omega_{rsm}$ can be readily obtained. $\Delta\dot{\omega}_{rsm}$ signal stems from $\Delta\omega_{rsm}$ and the additional diffrentiator block (DB) shown in Fig. 5. Thus, two input signals of the proposed FLC become available. The output control signal(U_s) is then injected to the summing point shown in Fig. 5.

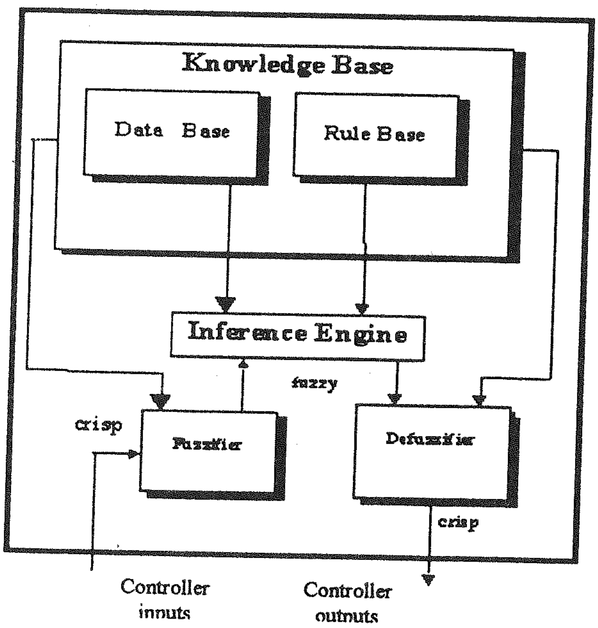


Figure (6) Schematic diagram of the FLC building blocks.

Each pair of the FLC input and output fuzzy variables ($\Delta\omega_{rsm}$, $\Delta\dot{\omega}_{rsm}$, U_s) is interpreted into the five linguistic fuzzy subsets varying from negative big (NB) to positive big (PB). Fig. 7 illustrates normalized synchronous Gaussian memebership functions related to $\Delta\omega_{rsm}$ and $\Delta\dot{\omega}_{rsm}$. The choice of these five member ship functions for each input fuzzy variable is based on the simulation studies of the sample system shown in Fig. 1 without functionality of any SVC scheme. The range of variations of the desired input variables ($\Delta\omega_{rsm}$ and $\Delta\dot{\omega}_{rsm}$) for the given plant without any voltage regulating device helped us to judge that the five membership functions are reasonably suitable for input variables.

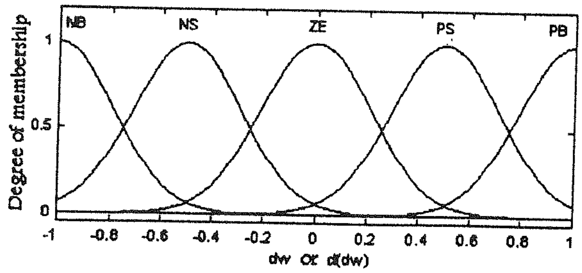


Figure (7) Normalized synchronous Gaussian membership functions for the first and second inputs ($\Delta\omega_{rsm}$, $\Delta\dot{\omega}_{rsm}$).

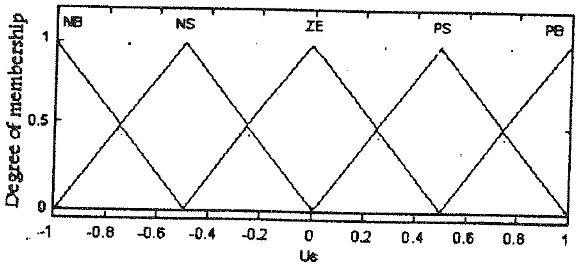


Figure (8) Normalized synchronous triangular membership functions for the uotput (U_s).

It is also understood that the five normalizd synchronous triangular membership functions given in Fig. 8 are appropriate for the controller output (U_s) in order to have more reasonable results and an easy real time implementation. The input gains (k1 and k2) and the output gain (k3) are normally used to properly scale the fuzzy input and output variables, respectively. In present study k1, k2 and k3 are assumed to main terminal voltage.

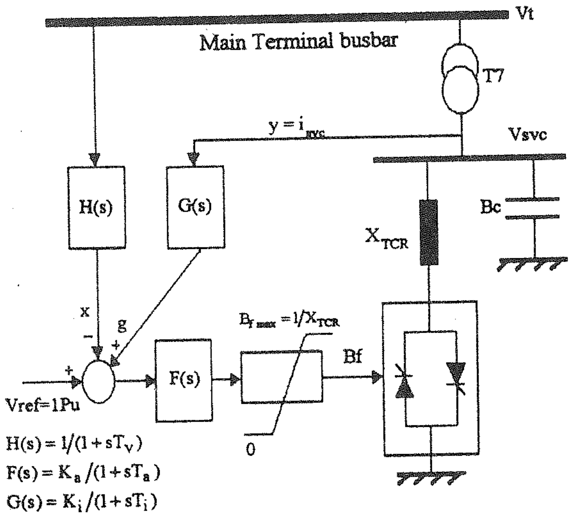


Figure (4) Schematic diagram of the CSVC.

In the second scheme shown in Fig.5 the proposed FLC represents as two inputs-single output non-linear controller. Both speed deviation ($\Delta\omega_{rsm}$) and associated acceleration ($\Delta\dot{\omega}_{rsm}$) of equivalent synchronous motor are taken as the inputs. In recent FLSVC, voltage feedback path (H(s)), firing angle regulator (F(s)) and limiter block are similar compared to the conventional one, while the currnt feedback path (G(s)) is vanished. It should be noted that the proposed FLSVC still consists of two feedback paths. The frist loop which is commonly known as the external feedback loop injects the cintrol single (U_s) to the summing point. This path is exited by the speed variations ($\Delta\omega_{rsm}$). The speed signal (i.e. ω_{rsm} shown in Fig. 5) is taken from synchronous motor shaft and its procedure is clarified in next section.

4-Fuzzy Logic-Based Static VAR Compensator (FLSVC)

The basic configuration of The FLC used in the proposed FLSVC shown in Fig. 6 is simply represented by four main parts : the fuzzifier, the knowledge base, the inference engine and the defuzzifier. The fuzzifier maps the FLC input crisp values scaled by input gains into fuzzy variables using normalized membership functions. The fuzzy control action based on the given fuzzy rule base. The fuzzy control action is in turn translated into proper crisp values scald by some appropriate output gains through the defuzzifier employing normalized membership functions [27].

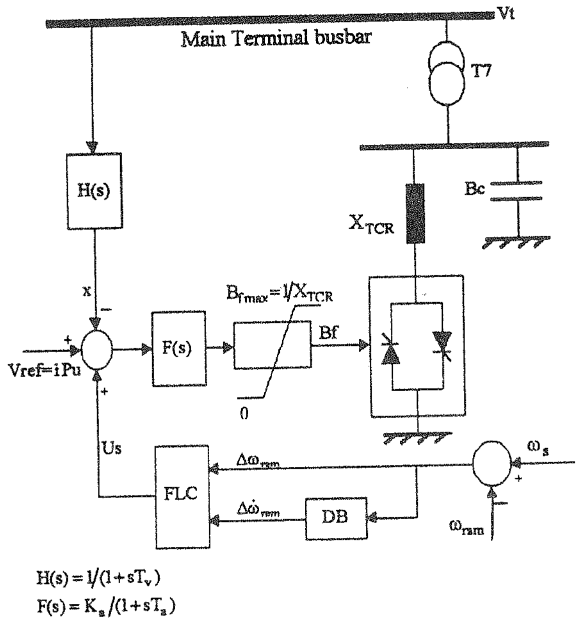


Figure (5) Schematic diagram of the FLSVC.

The feature of constant speed operation makes it even more complex for synchronous motors to obtain operation continuity in the presence of voltage disturbances, therefor the speed deviation ($\Delta\omega_{rsm}$) and the associated acceleration ($\Delta\dot{\omega}_{rsm}$) of the equivalent synchronous motors (ESM) are closen as the FLC inputs. Due to similarity of all synchronous motors in the given plant, $\Delta\omega_{rsm}$ and $\Delta\dot{\omega}_{rsm}$ of each synchronous motor would be similar to those of the ESM. Hence, in practice $\Delta\omega_{rsm}$ and $\Delta\dot{\omega}_{rsm}$ related to one of these synchronous motors should be used as winding), and mechanical part by a second-order system. The mathematical description of this dq model for three phase synchronous motors which is available in POWER LAB software is fully described in [24].

3-2-Three Phase Cage asynchronous Motor Model

The ESCAM which is also shown in Fig. 1 is represented in the rotating dq frame of reference enviroment. The electrical part of the machine is represented by a fourth state-space model (i.e. two coils for rotor and stator winding respectively), and the mechanical part by a second-order system. This dq model which is available in POWER LAB software is fully presented in [24].

3-3-Shunt DC Motors

In present study the general model of DC motor available in POWER LAB software is used in shunt mode of operation. Fig. 2 illustrates the block diagram of the employed model is well presented in [24].

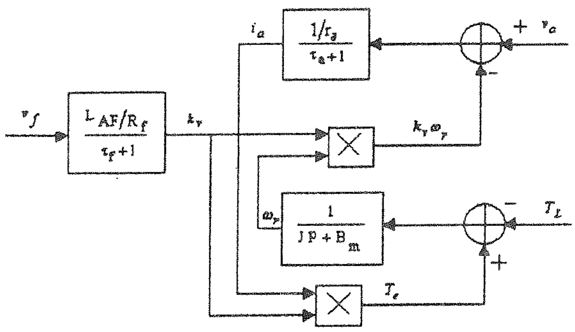


Figure (2)Shunt DC motor block diagram.

3-4-Transmission Line, Transformer and Statice Load Modeling

Each transmission line and/or transformers given in Fig. 1 is represented by a series resistance and reactance respectively, which is quite suitable to handle by POWER LAB software. The equivalent three phase static load (ESL) shown in Fig. 1 is also represented by series RL element to be suitable for employed software.

3-5-AC/DC Drive Model

The EDCM shown in Fig. 1 is fed by a transformer (T5) via three phase full wave AC/DC drive. Fig. 3 shows the schematic diagram for employed AC/DC drive for EDCM. The POWER LAB software consists of a comprehensive model for thyristors including the snubber circuit. Therefore the AC/DC drive modeling can be achieved by connecting the thyristors by fashionable manner for simulation purposes.

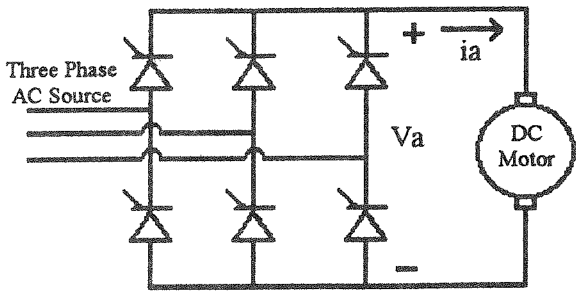


Figure (3) Three phase AC/DC full wave rectifier.

3-6-The SVC Model

The SVC shown in Fig. 1 is a three phase thyristor controlled reactor/fixed capacitor type (TCR/FC). In this paper, two distinct control strategies have been employed for comparative digital simulation. The first scheme, which is commonly referred to conventional SVC (CSVC), is shown in Fig. 4 [10,11]. The CSVC includes voltage and current feedback path (i.e. H(s) and G(s)), firing angle regulator (F(s)), and the associated limiter block as well. The two feedback paths shown in Fig. 4 act similar to a PID controller because the total current of the SVC (i.e. sum of the currents of reactor and capacitor) is proportional to integral and derivative of the three phase studied industrial power system. To feed the main terminal busbar of the load center, the remote external network is connected to a step-up transformer (T1), a double circuit transmission line (L1, L2), and a step-down transformer (T2). In the present study, the plant consists of several similar single cage asynchronous, group of unique rating synchronus as well as, number of similar shunt DC motors. Due to their similitaries including mechanical load torque and duty cycles, the synchronous motors can be justifiably assumed to be coherent [23]. As a result, they may be represented by an equivalent three phase synchronous motor (ESM) fed by a step-down transformer (T4). The same argument can be implemented for group of similar three phase single cage asynchronus and DC motors. Thus, two equivalent machines (ESCAM,EDCM) shown in Fig. 1 are sufficient for present study.

Furthermore, it is assumed that the plant also includes group of similar static loads which is considered to act as an eqiuvalent three phase static loads (ESL) supplied by an additional transformer (T6). The SVC, which is connected to the main terminal busbar via an auxiliary transformer (T7) is a three phase thyristor controlled reactor/fixed capacitor type (TCR/FC).

3-System Modeling

In this paper MATLAB subsidaries including POWER LAB, SIMULINK and FUZZY LOGIC TOOLBOX have been used for simulation of sample system shown in Fig. 1. Therefore the models employed for electrical motors, transmission lines, transformers and AC/DC drive are compatible to those available in POWER LAB software.

3-1-Three Phase Synchronous Motor Model

The ESM shown in Fig. 1 is represented in the rotor reference frame (dq frame). The electrical part of the machine is represented by fifth-order state space model (i.e. two coils for stator winding, one coil for rotor field winding and tow coils for rotor damper

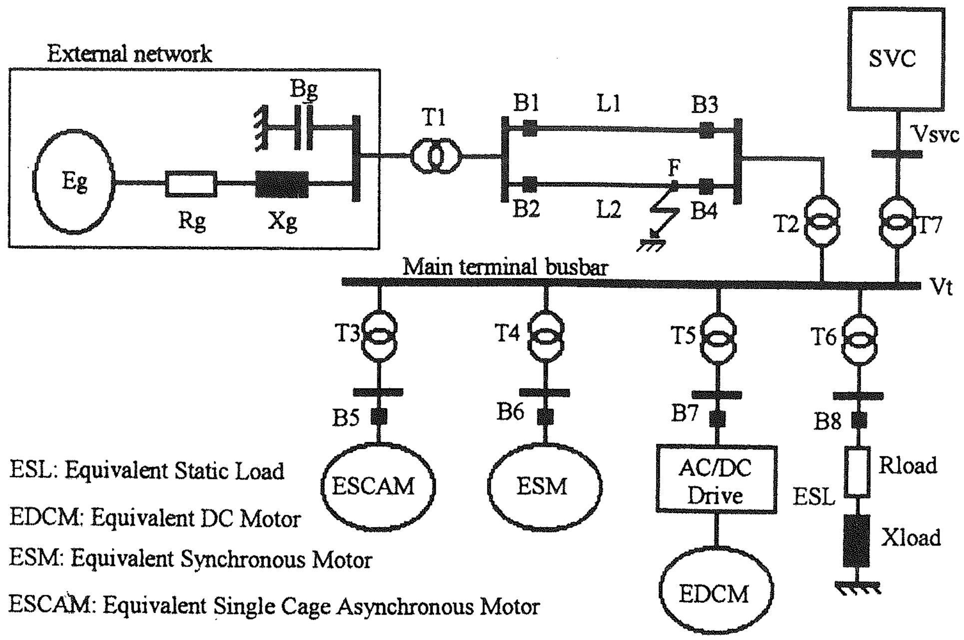


Figure (1) The sample system single line diagram.

have been applied for enhancing the operation continuity while it is necessary to consider preventive measures to minimize the risk of motor damage. The tecnique of riding through momentary voltage dips by keeping motors connected to their source during a voltage sag can minimize potential harmful effects to the motors and enhance oparation reliability [8]. This technique can be further improved by voltage stabilization at the point of service by installing a SVC.

In large industrial installation, voltage drops due to motor starting may also occur for a certain interval of time. Various studies [9,10] have proved that the SVCs can also be applied to start larg three phase electrical motors, since they support the voltage and start-up torque and minimize the start- up time. These studies prove that the fast controllable injection of reactive power by SVCs not only decreases the inrush start-up currents but also makes the reactive power demand to a certain minimum level during running conditions. Moreover, the continuose voltage support reduces the R^2I losses. This is because of the decrease in motor reactive power demand with an increase in its terminal voltage [11].

Industrial power system are highly non-linear and stochastic in nature. Therefore, the controller parameters of a specific regulating device can be optimum for one set of operating conditions but may not be suitable for another circumstances. Therefore, various investigators are studying how to use modern control techniques to improve the overall system performance.

As a well suited alternative to classical control strategies, the FLC has been suggested as an appropriate choice to control nonlinear systems [12]. The basic feature of FLCs is that the control strategy can be simply expressed by a set of fuzzy rules, which describe the behaviour of controller by employing linguistic terms. From these rules, the proper control action is then inferred. In addition , FLCs are relatively easy to develop and simple to implement.

Some investigations have been performed in the area of application of FLCs in electric power systems [13-17]. The implementation of classical controllers for static VAR compensator within an AC motors plant is also seen in [11,18-2], however the application of fuzzy logic based static VAR compensator (FLSVC) for AC motor loads is introduced in our previous work [22]. The main objective of present study is to enhance the voltage profile and overall dynamic performance of an industrial utilization consisting of AC and DC motor loads by installing the FLSVC close to the load center. In fact this paper is the extension of our previous work [22].

For the current study, the FLC with two input signals is employed, while the output control signal is injected to the SVC voltage regulator. The performance of the proposed FLSVC is examined by several non-linear time-domain simulation tests. these tests have been performed in different operation conditions and disturbances such as motor startting, loading and momentary voltage dips.

The results show that the FLSVC remarkably improves the voltage profile and the overall system performance over the wide range operating conditions compared to those of the system, which is equipment with the best conventional SVC(CSVC) that we could design for a specific operation point.

2-System Description

Fig. 1 shows the single line diagram of

Fuzzy Logic Based Static VAR Compensators for Enhancing the Performance of AC and DC Motor Loads

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Abstract

The paper presents a simple yet powerful fuzzy logic based static VAR compensator (FLSVC) applied to an industrial power network consisting of three phase synchronous, asynchronous and DC motor loads. In the proposed fuzzy logic controller (FLC), the speed and acceleration variations of a specific machine are taken as the inputs. To demonstrate the effectiveness and capabilities of the employed FLSVC, several nonlinear time domain digital simulation tests are performed. The results show that over a wide range of operating conditions and disturbances, the FLSVC improves remarkably the voltage profile and the overall dynamic performance.

Keywords

Fuzzy logic controller, Static VAR compensator,Single cage Asynchronous motor, Synchronous motor, DC motor

1-Introduction

Most voltage problems associated with sensitive equipment are related to momentary voltage dips, which can occur due to faults in the supply system. The inability of sensitive equipment to function properly in the presence of momentary voltage sags raised a serious concern [1-3]. General measures to minimize the effects of momentary voltage dips, such as the addition of generating capacity and the reduction of system impedance, have major cost implications.

The effect of momentary voltage dips on the proper functioning of a particular sensitive equipment may be minimized by installing a fast response voltage regulator at the point of service. This type of regulator includes static VAR compensator (SVC) [4-6] characterized by a fast response time and virtually unlimited life as well. The general idea of applying a voltage reguletor (i.e.SVC) is to optimally stabilize the equipment voltage during and immediately after the momentary disturbance of supply voltage so that the satisfactory functioning of the equipment is preserved.

The operation continuity of the sensitive equipment composed of synchronous and asynchronous motor loads subjected to unavoidable momentary voltage dips is of particular interest [7, 8]. Traditional practice such as reclosing and bus - transfer schemes