

MATHEMATICAL MODELING of UPQC

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1. Active Power Filter

Active Power filters have wide application in modern electrical distribution system for eliminating the harmonics associated with it. The Shunt active power filter (SAPF) is one of power filters which have better dynamic performance and it needs an accurate control algorithm that provides robust performance. The control methods are responsible for generating the reference currents which used to trigger the Voltage Source Inverters (VSI).

Need of Active Power filter is Due to harmonic injection in power system due to various nonlinear loads such as uninterruptible power suppliers (UPS), adjustable speed drives (ASD), furnaces and single phase computer power supply etc. has resulted serious power quality problems. Most of these of non-linear loads cause harmonic injection into the power system and degrade the system performances and lower the system efficiency.

Topologies of Active power filter:

- Shunt Active Power Filter and
- Series Active power Filter

2. Basic Configuration of UPQC

Fig. 1 shows system configuration of a three-phase UPQC. The key components of UPQC are as follows:

Series Active Power Filter: It is a voltage-source inverter connected in series with AC line through a series transformer and acts as a voltage source to mitigate voltage distortions. It eliminates supply voltage flickers and imbalances from the load terminal voltage. Control of the series inverter output is performed by using pulse width modulation (PWM).

Among the various PWM technique, the hysteresis band PWM is frequently used because of its ease of implementation. Besides fast response, the method does not need any knowledge of system parameters.

Shunt Active Power Filter: It is a voltage-source inverter connected in shunt with the same AC line which acts to cancel current distortions, compensate reactive current of the load and improve the power factor of the system. It also performs the DC-link

voltage regulation, resulting in a significant reduction of the DC capacitor rating.

The output current of shunt converter is adjusted using a dynamic hysteresis band by controlling the status of the semiconductor switches such that output current follows the reference signal & remains in a pre-determined hysteresis band.

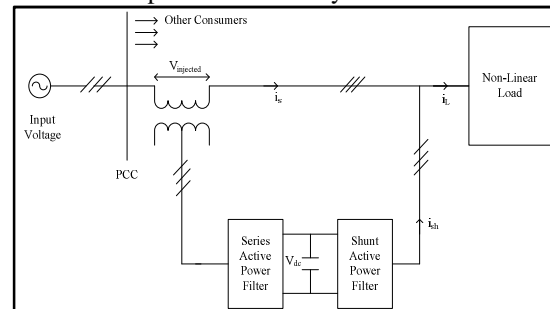


Figure.1 Basic Configuration of UPQC

DC capacitor: The voltage across this capacitor provides the self-supporting DC voltage for proper operation of both the inverters. With proper control, the DC link voltage acts as a source of active as well as reactive power and thus eliminates the need of external DC source like battery. Two voltage source inverters are connected with this DC capacitor.

Low-pass filter: It is used to attenuate high-frequency components of the voltages at the output of the series converter that are generated by high-frequency switching of VSI.

High-pass filter is installed at the output of shunt converter to absorb ripples produced due to current switching.

Series Injection Transformer: The harmonic compensated voltage generated by the Series active filter for maintaining the pure sinusoidal voltage is injected into the line through this transformer. Turns ratio is also important aspect for control of current flowing through the series inverter.

The power circuit of active power filter consists of energy storage unit, passive filter and DC to AC inverter. DC link voltage should be higher than maximum peak of the supply voltage. DC link

voltage can be controlled using proportional-integral-derivative (PID) controller, PI controller and fuzzy logic.

Series active filter connected in series with a transformer, acts as controlled voltage supply and can compensate all voltage related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc. On the other hand, Shunt active filter is connected across the load, acts as controlled current source and compensate reactive power, current unbalance and harmonics.

3. Modeling of UPQC

Shunt Active Filter

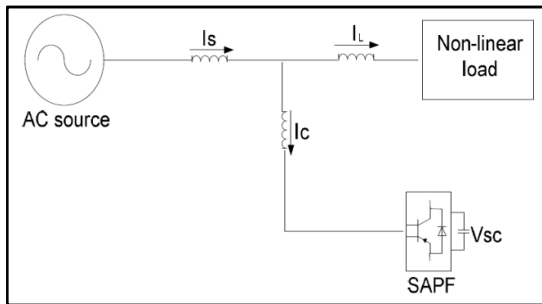


Figure 1 Shunt Active Filter

Fig.2 shows the basic block diagram of the shunt active filter, it is highly reliable with adequate compensation abilities. Shunt active filter has the capability for compensating load harmonic currents and reactive power requirement of the non-linear loads in power network. It is connected in parallel to power system network at a point of common coupling (PCC) between supply authority and consumers.

System Configuration

The configuration model of shunt active power filter using a voltage source converter (VSC) is shown in Fig.3 .In this model; the resistance R_{dc} in series with the voltage source inverter represents the sum of the coupling inductor resistance losses and the inverter conduction losses. The inductance L_f represents the leakage inductance of the coupling inductor. The sum of the switching losses of the inverter and the power losses in the capacitor is represented by R_{dc} which is in shunt with the DC-link capacitor C_{dc} . In Fig. 3, V_{fa} , V_{fb} , and V_{fc} are the three-phase Shunt Active Power Filter output voltages; V_{La} , V_{Lb} , and V_{Lc} are the three phase bus voltages at load-side; i_{fa} , i_{fb} , and i_{fc} are the three-phase Shunt Active Power Filter output currents.

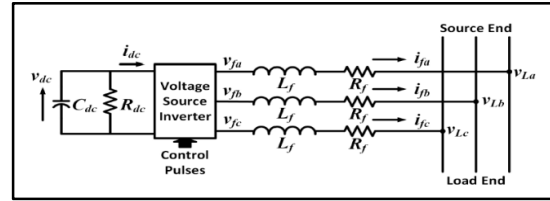


Figure. 2Equivalent Circuit of SAPF

Modeling of Shunt Active Filter

In order to analyse the balanced three-phase system more conveniently, the three-phase voltages and currents are converted to synchronous rotating frame by $abc/dq0$ transformation. The dq -frame rotate with an angle $\theta = \omega t$ from the reference axis of the abc -frame. By this transformation, the control problem is greatly simplified since the system variables become DC values under the balanced condition. The transformation from phase variables to d and q coordinates is given as follows :

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = T \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

Where,

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

A linear mathematical model for each phase of the SAPF shown in Fig.1 can be written as:

$$\begin{aligned} L_f \frac{di_{fa}}{dt} &= -R_f i_{fa} + V_{fa} - V_{La} \\ L_f \frac{di_{fb}}{dt} &= -R_f i_{fb} + V_{fb} - V_{Lb} \end{aligned} \tag{2}$$

$$L_f \frac{di_{fc}}{dt} = -R_f i_{fc} + V_{fc} - V_{Lc}$$

Equations (2) can be written in following form:

$$L_f \frac{d}{dt} \begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix} = -R_f \begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix} + \begin{bmatrix} V_{fa} \\ V_{fb} \\ V_{fc} \end{bmatrix} - \begin{bmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{bmatrix} \tag{3}$$

With dq -transformation from equation (1),

$$\begin{aligned} L_f \frac{d}{dt} \left(T^{-1} \begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{f0} \end{bmatrix} \right) &= -R_f T^{-1} \begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{f0} \end{bmatrix} + T^{-1} \begin{bmatrix} V_{fd} \\ V_{fq} \\ V_{f0} \end{bmatrix} \\ &\quad - T^{-1} \begin{bmatrix} V_{Ld} \\ V_{Lq} \\ V_{L0} \end{bmatrix} \end{aligned}$$

The above equation can be simplified as:

$$L_f T \left(\frac{d}{dt} (T^{-1}) \begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{f0} \end{bmatrix} + (T^{-1}) \frac{d}{dt} \begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{f0} \end{bmatrix} \right) = -R_f \begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{f0} \end{bmatrix} + \begin{bmatrix} V_{fd} \\ V_{fq} \\ V_{f0} \end{bmatrix} - \begin{bmatrix} V_{Ld} \\ V_{Lq} \\ V_{L0} \end{bmatrix} \quad (4)$$

Where,

$$\frac{d}{dt} (T^{-1}) = \omega \sqrt{\frac{2}{3}} \begin{bmatrix} -\sin \theta & \cos \theta & 0 \\ -\sin(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) & 0 \\ -\sin(\theta + \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) & 0 \end{bmatrix}$$

$$T \cdot \frac{d}{dt} (T^{-1}) = \omega \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\frac{d\theta}{dt} = \omega$$

Applying all the above relation in equation (4)

$$\frac{d}{dt} \begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{f0} \end{bmatrix} = \begin{bmatrix} \frac{-R_f}{L_f} & \omega & 0 \\ -\omega & \frac{-R_f}{L_f} & 0 \\ 0 & 0 & \frac{-R_f}{L_f} \end{bmatrix} \begin{bmatrix} i_{fd} \\ i_{fq} \\ i_{f0} \end{bmatrix} + \frac{1}{L_f} \begin{bmatrix} V_{fd} \\ V_{fq} \\ V_{f0} \end{bmatrix} - \frac{1}{L_f} \begin{bmatrix} V_{Ld} \\ V_{Lq} \\ V_{L0} \end{bmatrix} \quad (5)$$

Suppose, the output voltage of the SAPF can be expressed as:

$$v_{fd} = K v_{dc} \cos \theta \quad (6)$$

$$v_{fq} = K v_{dc} \sin \theta \quad (7)$$

Where K is a factor that relates the DC voltage to the peak phase-to-neutral voltage on the AC side; v_{dc} is the DC-link voltage; α is the phase angle which the SAPF output voltage leads the bus voltage.

Using the relation (6) and (7), the equation (5) can be modified as

$$\frac{d}{dt} \begin{bmatrix} i_{fd} \\ i_{fq} \end{bmatrix} = \begin{bmatrix} \frac{-R_f}{L_f} & \omega & \frac{K \cos \alpha}{L_f} \\ -\omega & \frac{-R_f}{L_f} & \frac{K \sin \alpha}{L_f} \end{bmatrix} \begin{bmatrix} i_{fd} \\ i_{fq} \end{bmatrix} - \frac{1}{L_f} \begin{bmatrix} V_{Ld} \\ V_{Lq} \\ V_{L0} \end{bmatrix} \quad (8)$$

From the SAPF input-output power balance equation, it can be written as:

$$p_{dc} = p_f$$

$$\text{Or, } v_{dc} i_c + v_{dc} i_R = v_{fa} i_{fa} + v_{fb} i_{fb} + v_{fc} i_{fc}$$

$$\text{Or, } v_{dc} C_{dc} \frac{dv_{dc}}{dt} + \frac{v_{dc}^2}{R_{dc}} = v_{fd} i_{fd} + v_{fq} i_{fq}$$

$$\text{Or, } \frac{dv_{dc}}{dt} = \frac{K \cos \alpha}{C_{dc}} i_{fd} + \frac{K \sin \alpha}{C_{dc}} i_{fq} - \frac{v_{dc}}{R_{dc} C_{dc}} \quad (9)$$

From the equations (8) and (9), the relation for the dynamic model of the SAPF can be derived and is given below:

$$\frac{d}{dt} \begin{bmatrix} i_{fd} \\ i_{fq} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R_f}{L_f} & \omega & \frac{K}{L_f} \cos \alpha \\ -\omega & \frac{-R_f}{L_f} & \frac{K}{L_f} \sin \alpha \\ \frac{K}{C_{dc}} \cos \alpha & \frac{K}{C_{dc}} \sin \alpha & \frac{1}{R_{dc} C_{dc}} \end{bmatrix} \begin{bmatrix} i_{fd} \\ i_{fq} \\ v_{dc} \end{bmatrix} - \frac{1}{L_f} \begin{bmatrix} v_{Ld} \\ v_{Lq} \\ v_{L0} \end{bmatrix} \quad (10)$$

4 Control Strategy for Shunt Active Filter

Instantaneous three-phase currents and voltages are transformed to α - β co-ordinates as shown in equation.

$$I_{\alpha} = \frac{2}{3} I_a - \frac{1}{3} (I_b - I_c) \quad (11)$$

$$I_{\beta} = \frac{2}{\sqrt{3}} (I_b - I_c) \quad (12)$$

$$V_{\alpha} = \frac{2}{3} V_a - \frac{1}{3} (V_b - V_c) \quad (13)$$

$$V_{\beta} = \frac{2}{\sqrt{3}} (V_b - V_c) \quad (14)$$

The source side instantaneous real and imaginary power components are calculated by using source currents and phase voltages as given in equation:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_{\alpha} & V_{\beta} \\ -V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} I_{\alpha} \\ I_{\beta} \end{bmatrix} \quad (15)$$

$I_{S\alpha}^*$ and $I_{S\beta}^*$ are the reference currents of shunt APF in α - β co-ordinates given by :

$$\begin{bmatrix} I_{S\alpha}^* \\ I_{S\beta}^* \end{bmatrix} = \frac{1}{v_{\alpha}^2 + v_{\beta}^2} \begin{bmatrix} V_{\alpha} & V_{\beta} \\ -V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} \bar{p} + P_0 + P_{loss} \\ 0 \end{bmatrix} \quad (16)$$

Two-axis stationary reference frame is converted to three phase reference frame.

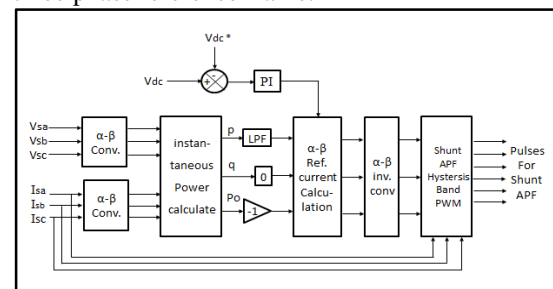


Figure. 3 Control Strategy of Shunt Active Filter

$$I_a^* = I_{S\alpha}^* \quad (17)$$

$$I_b^* = \frac{-I_{S\alpha}^* + \sqrt{3} I_{S\beta}^*}{2} \quad (18)$$

$$I_c^* = \frac{-I_{S\alpha}^* - \sqrt{3} I_{S\beta}^*}{2} \quad (19)$$

These reference source current signals are then compared with sensed three-phase source currents,

and the errors are processed by hysteresis band PWM controller to generate the required switching signals for the shunt APF switches.

4. Design of Coupling Inductor for Shunt Active Filter

Coupling Inductor for Shunt Active Filter range is expressed as:

$$\frac{V_{dc}}{8f_s(\text{Level}-1)\Delta I_r} \leq L \leq \frac{\delta_v V_{dc}}{r\omega I_c} \quad (20)$$

Where V_{dc} represent the Dc bus voltage, f_s is the switching frequency, ΔI_r is maximum load current, I_c is the current rating of the APF and r is suggested to select the order of the most significant harmonics in the load currents.

When the final value of the inductor is determined, it is suggested to select a value close to the lower boundary. The value close to the lower boundary could provide better current tracking speed with acceptable current ripples. A smaller inductor also reduces the cost. However, it is suggested to still test the final value by estimating the upper boundary according to (21). In some cases, the obtained upper limit of the inductor value is smaller than the lower limit. It indicates conflicts exist in the requirement of current tracking speed and suppressing current ripple. Some approaches, such as increasing PWM frequency and adopting multi-level VSI, could be considered to reduce the lower boundary.

From above equation (21), $L_{min} = \frac{V_{dc}}{8f_s(\text{Level}-1)\Delta I_r}$

for Duty Ratio, $D = \frac{1}{2}$ But we know that Duty ratio varies between 0 and 1.

$$L_{min} = \frac{V_{dc}}{4f_s(\text{Level}-1)\Delta I_r} \text{ for Duty Ratio, } D=1 \quad (21)$$

5. Series Active Filter

The source is connected to the non-linear load. Due to this nonlinear load the source voltage becomes distorted. The Series filter is used to eliminate voltage harmonics and to balance and regulate the terminal voltage of the load. The series filter is connected through a transformer. The controller pulses for the series active filter are given through the pulses obtained by the controller circuit. The series APF is expected to provide compensation for

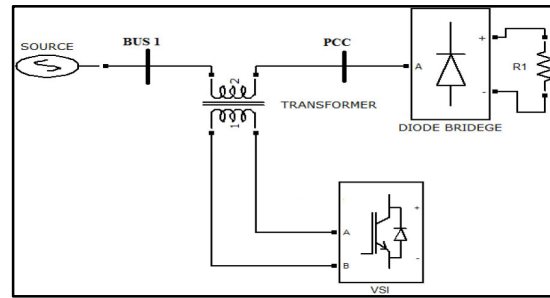


Figure. 4 Series Active Filter

The harmonic and reactive portion of the three-phase voltage, this ensures purely sinusoidal voltage waveform at the load end .

Control strategy of Series Active Filter

These produced three-phase load reference voltages are compared with load line voltages and errors are then processed by sinusoidal PWM controller to generate the required switching signals for series APF IGBT switches as shown in Fig.6

A series filter is used for compensation of voltage harmonics, sag, swell and reactive power in a three phase system even with unbalanced source condition. Series filter uses different control algorithms new control strategy is proposed for the series active filter. The sensed source and actual filter voltage is given as the input of the controller and the source voltage is given to a second order low pass filter in order to extract the fundamental component with a phase shift of 90° . A phase shifter circuit is used in order to eliminate the phase shift. Peak value of the fundamental component of the source voltage is calculated using a peak detector circuit. The phase shifted and the peak detector output is given to a divider circuit and a unit amplitude sine wave is obtained. The output of the divider circuit is multiplied with a constant value which is the required voltage at bus bar. The multiplier output and the source voltage is given to a subtraction and reference filter voltage is obtained. The filter voltage is compared with the actual voltage and the pulses for the filter are obtained. Hysteresis controller is used to generate the pulses for the series filter.

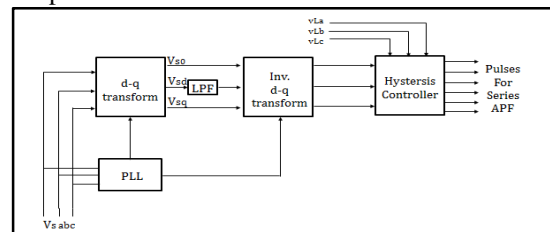


Figure. 5 Control Strategy of Series Active Filter

The instantaneous reactive power algorithm (IRPT) is based on Clarke's transformation. The voltage and current vectors in phase is transferred to $\alpha\beta$ coordinates. The instantaneous reactive power

algorithm (IRPT) is based on Clarke's transformation. The voltage and current vectors in phase is transferred to $\alpha\beta$ coordinates.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (22)$$

v_α and v_β represents the mains voltage at α and β axis. V_a, V_b and V_c represents the mains voltage in a, b and c phase respectively.

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (23)$$

i_{La}, i_{Lb} and i_{Lc} represents the load current in a, b and c phase respectively. $i_{L\alpha}$ and $i_{L\beta}$ represents the load current in α and β axis. The real and reactive power for the load can be calculated by the voltage and current in α - β coordinates.

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} i_{L\alpha} & i_{L\beta} \\ i_{L\beta} & -i_{L\alpha} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (24)$$

p_L and q_L are the instantaneous real and imaginary power consumed by the load. The p_L and q_L contain both dc term and ac term. But for voltage harmonic suppression and reactive power compensation, the ac term of p_L and ac and dc term of q_L should be provided by the active power filter. So the reference signal of the compensation voltage can be represented as

$$\begin{bmatrix} v_{c\alpha^*} \\ v_{c\beta^*} \end{bmatrix} = \begin{bmatrix} i_{L\alpha} & i_{L\beta} \\ i_{L\beta} & -i_{L\alpha} \end{bmatrix}^{-1} \begin{bmatrix} p_{Lac} \\ q_L \end{bmatrix} \quad (25)$$

The reference signal of the compensation voltage is obtained by transferring $v_{c\alpha^*}$ and $v_{c\beta^*}$ to three phase system using inverse Clarke transformation.

$$\begin{bmatrix} v_{c\alpha^*} \\ v_{c\beta^*} \\ v_{c\gamma^*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{c\alpha^*} \\ v_{c\beta^*} \end{bmatrix} \quad (26)$$

Where $v_{c\alpha^*}, v_{c\beta^*}$ and $v_{c\gamma^*}$ represents the reference filter voltages in a, b and c phases respectively.

Control Algorithm

The series active filter is one type of active filter used to eliminate the voltage unbalance and harmonics. Different types of control methods are used to control the series filter. The choice of the control algorithm decides the accuracy and the speed of response of filter.

The compensation characteristic becomes ideal when the active filter presents an infinite impedance, $k=\infty$. The active filter must generate a voltage proportional to harmonic component of the source current, which is calculated by applying the

vactorial theory of the electric power. The reference current is calculated as follows

$$i_{ref} = i_1 - \frac{p}{v^2} V \quad (27)$$

Where, i_1 = current vector of the load

P-average power defined by

$$P = \frac{1}{T} \int_0^T (u^T \cdot i) dt \quad (28)$$

u = Voltage vector before active filter.

V = Voltage vector of direct sequence.

v^2 = Norm of v defined by

$$v^2 = \frac{1}{T} \int_0^T (V^T \cdot V) dt \quad (29)$$

T is the fundamental period and “.” denotes the dot product of the vector.

The reference voltage to compensate the voltages unbalance is obtained by calculating the zero and inverse sequence components from equation. The active filter must generate this components, but in inverse phase. Applying the inverse of the Fortes cue transformation, the following equations are obtained.

$$\begin{bmatrix} v_{ref a} \\ v_{ref b} \\ v_{ref c} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} -v_{a0} \\ 0 \\ -v_{a2} \end{bmatrix} \quad (30)$$

Where v_{a0} is the zero sequence component and v_{a2} the negative sequence component.

Fig.4 shows the control scheme for obtaining the reference single. The voltage compensation single is generated by the PWM inverter. The gain K_v is the turn ratio of series transformer, which is applied to the reference signal for the voltage unbalance. The gain K_i is the proportional constant for the harmonics of the source current; it gets the magnitude of the impedance for high frequency. Thus, the inverter must generate compensation signal as follow as,

$$V_c = K_i I_{ref} + K_v V_{ref} \quad (31)$$

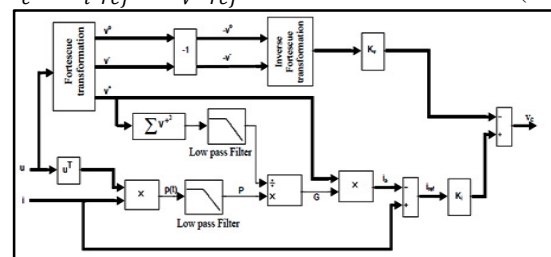


Figure 6 Control Scheme for series Active Filter
The gating signals of the inverter are generated by comparing the resultant reference signal with the output of the inverter through a bang-bang control.

6. Introduction to FLC

Fuzzy logic has rapidly become one of the most successful of today's technology for developing sophisticated control system. With it aid complex requirement so may be implemented in amazingly simple, easily minted and inexpensive controllers. The past few years have witnessed a rapid growth in number and variety of application of fuzzy logic.

The application range from consumer products such as cameras, camcorder, washing machines and microwave ovens to industrial process control, medical instrumentation, and decision support system. Many decision-making and problem solving tasks are too complex to be understood quantitatively however, people succeed by using knowledge that is imprecise rather than precise. Fuzzy logic is all about the relative importance of precision. Fuzzy logic has two different meanings in narrow senses; fuzzy logic is a logical system which is an extension of multi valued logic. but in wider sense fuzzy logic is synonymous with the theory of fuzzy sets. Fuzzy set theory is originally introduced by Lotfi Zadeh in the 1960s resembles approximate reasoning in its use of approximate information and uncertainty to generate decisions.

Several studies show, both in simulations and experimental results, that Fuzzy Logic control yields superior results with respect to those obtained by conventional control algorithms thus, in industrial electronics the FLC control has become an attractive solution in controlling the electrical motor drives with large parameter variations like machine tools and robots. However, the FLC design and tuning process is often complex because several quantities, such as membership functions, control rules, input and output gains, etc. must be adjusted. The design process of a FLC can be simplified if some of the mentioned quantities are obtained from the parameters of a given Proportional-Integral controller (PIC) for the same application.

Motivations for choosing fuzzy logic controller (FLC)

- Fuzzy logic controller can model nonlinear systems. If an accurate mathematical model is available with known parameters it can be analysed, for example by bode plots or Nyquist plot, and controller can be designed for specific performances. Such procedure is time consuming.
- Fuzzy logic controller has adaptive characteristics. The adaptive characteristics can achieve robust performance to system with uncertainty parameters variation and load disturbances.

Fuzzy logic controller (FLC)

Fuzzy logic expressed operational laws in linguistics terms instead of mathematical equations. Many systems are too complex to model accurately, even with complex mathematical equations; therefore traditional methods become infeasible in these systems.

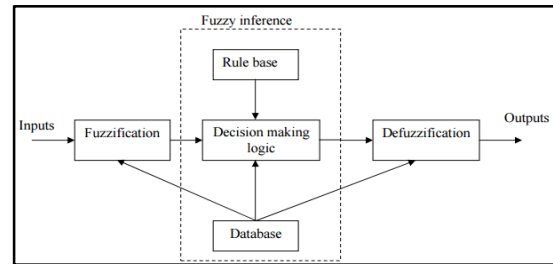


Figure. 7 Structure of Fuzzy logic controller

However fuzzy logics linguistic terms provide a feasible method for defining the operational characteristics of such system. Fuzzy logic controller can be considered as a special class of symbolic controller. The configuration of fuzzy logic controller block diagram is shown in Fig. 8.

The fuzzy logic controller has three main components

1. Fuzzification
2. Fuzzy Inference
3. Defuzzification

Fuzzification

The **Fuzzification** comprises the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term.

Example: For the Fuzzification of the car speed value $x_0 = 70$ km/h the two membership functions μ_A and μ_B from Figure can be used, which characterize a low and a medium speed fuzzy set, respectively. The given speed value of $x_0 = 70$ km/h belongs with a grade of $\mu_A(x_0) = 0.75$ to the fuzzy set "low" and with a grade of $\mu_B(x_0) = 0.25$ to the fuzzy set "medium".

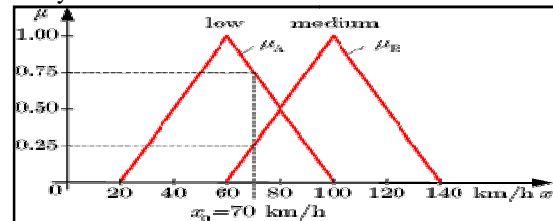


Figure. 8 Fuzzification of a car speed

Fuzzification creates the input parameters to a fuzzy controller. A fuzzy controller must have two input parameters. One is the error and the second is the rate of change of error. The fuzzy parameters of error (command-feedback) and error-dot (rate-of-change-of-error) were modified by the adjectives "negative", "zero", and "positive".

To picture this, imagine the simplest practical implementation, a 3-by-3 matrix. The columns represent "negative error", "zero error", and "positive error" inputs from left to right. The rows represent "negative", "zero", and "positive" "error-dot" input from top to bottom. This planar construct is called a rule matrix. It has two input conditions,

"error" and "error-dot", and one output response conclusion (at the intersection of each row and column).

Although not absolutely necessary, rule matrices usually have an odd number of rows and columns to accommodate a "zero" center row and column region. This may not be needed as long as the functions on either side of the center overlap somewhat and continuous dithering of the output is acceptable since the "zero" regions correspond to "no change" output responses the lack of this region will cause the system to continually hunt for "zero". It is also possible to have a different number of rows than columns. This occurs when numerous degrees of inputs are needed. The maximum number of possible rules is simply the product of the number of rows and columns, but definition of all of these rules may not be necessary since some input conditions may never occur in practical operation.

The primary objective of this construct is to map out the universe of possible inputs while keeping the system sufficiently under control.

Fuzzy Inference

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves all of the pieces that are described in the previous sections: membership functions, fuzzy logic operators, and if-then rules. There are two types of fuzzy inference systems that can be implemented Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined. Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. Mamdani's method was among the first control systems built using fuzzy set theory.

After the aggregation process, there is a fuzzy set for each output variable that needs Defuzzification. It is possible, and in many cases much more efficient, to use a single spike as the output membership functions rather than a distributed fuzzy set. This is sometimes known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set.

It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of a two-dimensional function. Rather than integrating across the two-dimensional function to find the centroid, we use the weighted average of a few data points. Sugeno-type systems support this type of model. In general, Sugeno-type systems can be used to model any inference system in which the

output membership functions are either linear or constant.

Defuzzification:

Defuzzification is the process of producing a quantifiable result in fuzzy logic. Typically, a fuzzy system will have a number of rules that transform a number of variables into a "fuzzy" result, that is, the result is described in terms of membership in fuzzy sets.

The various defuzzification methods involved for getting back the crisp values are as follows:

- Centroid Average (CA)
- Maximum Centre Average (MCA)
- Mean of Maximum (MOM)
- Smallest of Maximum (SOM)
- Largest of Maximum (LOM)

Centroid Average and Maximum Centre Average methods belong to continuous ones and are used in control engineering applications and process modeling. The rest represent discontinuous methods which are used for pattern recognition for selecting the alternative.

Fuzzy implication methods:

Mamdani or Max-min method

The max-min algorithm operates on each rule and combining all the rule. In min composition, for each rule, the algorithm matches the membership degrees to the antecedent membership function and finds the minimum. The minimum function is equivalent of the AND logical function.

In the max composition, the combined output fuzzy is constructed by taking the maximum over all of the fuzzy assigned to the output variables by the inference rule. The maximum of each column is then calculated, which yields a composite or inferred membership function that is then passed to the defuzzification procedure.

Advantages of the Mamdani Method

- It is intuitive.
- It has widespread acceptance.
- It is well suited to human input.

2. Sugeno Method

The Takagi-sugeno fuzzy model (Takagi and sugeno 1985) uses crisp functions as the consequence of the rules. This is the difference between the Mamdani and sugeno method. A takagi-sugeno rule set has the general form:

RULE 1: *IF* x is A_i *THEN* $y_i = f_i(x_0)$, $i=1, 2, \dots, n$.

The antecedent of each rule is a set of fuzzy proposition connected with the AND operator. By means of the fuzzy sets of the antecedent positions the input domain is softly partitioned into smaller regions where the mapping is locally approximated by the crisp function f_i . Takagi- sugeno rule aggregation and their effects differ from the Mamdani method. One variation of the Takagi-sugeno system uses the weighted mean criterion to

combine all the local representations in a global approximator.

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

Advantages of the Sugeno Method

- It is computationally efficient.
- It works well with linear techniques (e.g., PID control).
- It is well suited to mathematical analysis

Steps for Fuzzy Logic controller

The general design procedure for fuzzy control can be given as follow:

1. First, analyze whether the problem has sufficient elements to warrant a fuzzy logic application; otherwise, apply a conventional method.
2. Get all the information (design and operation characteristics of the plant) from the operator of the plant to be controlled.
3. If model is available, develop a simulation model and study the performance characteristics.
4. Identify the function elements where fuzzy logic can be applied.
5. Identify the input and output variables of each fuzzy system.
6. Formulate the fuzzy sets and select the corresponding membership function shape of each.
7. Formulate the rule table.
8. Test the model, evaluate the results, tune the rules and membership functions, and retest until satisfactory results are obtained.

7. MEMBERSHIP FUNCTION

The variables chosen for this controller are dc voltage (V_{dc}) and constant reference voltage. The membership function maps the crisp values into fuzzy variables. The triangular membership functions are used to define the degree of membership. The degree of membership plays an important role in designing a fuzzy controller. Each of the input and output fuzzy variables is assigned five linguistic fuzzy subsets varying from Negative Big (NB) to Positive Big (PB). Here triangular membership function is used for both input and output. The range of input-1(Dc voltage, V_{dc}) is [0 620] and input-2 (constant reference voltage, 600) is [0 600] and output (P_{loss}) is [-20 600] the membership function is [-20 600]. The five

membership function for fuzzy variable is listed below:

Table 1 Membership functions for fuzzy variables

The membership function for two inputs and one output is shown below:

Fig 10 shows the membership function for Dc Voltage V_{dc} which is taken as Input-1.

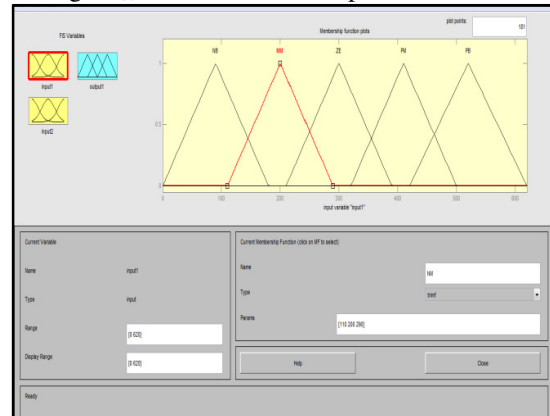


Figure.9 Membership function for V_{dc} (Input-1)

Fig 11 shows the membership function for reference constant which is taken as Input-2.

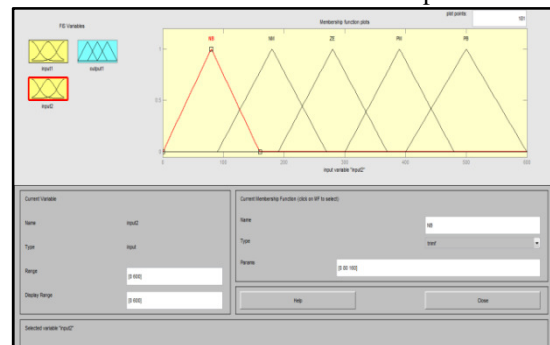


Figure 10 Membership function for Constant reference (Input-2)

Fig 12 shows the membership function for Power loss P_{loss} which is taken as Output.

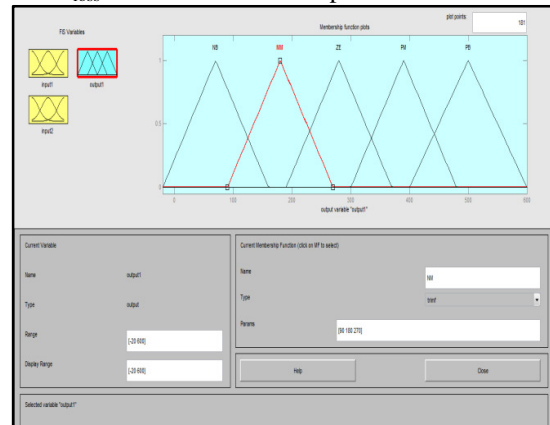


Figure.11 Membership function for Power Loss (Output)

Fig.13 shows the Rule viewer of Input and Output Membership function.

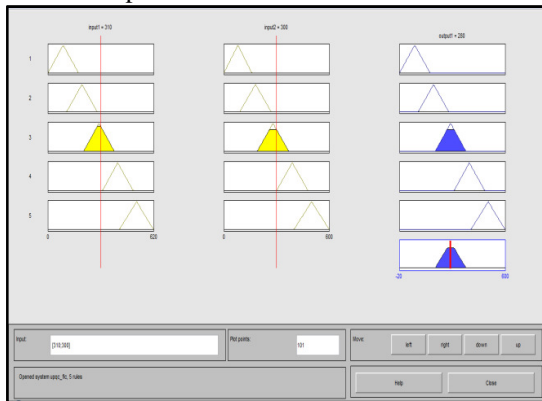


Figure.12Rule Viewer of Membership function

The Rule Viewer displays, in one screen, all parts of the fuzzy inference process from inputs to outputs. Each row of plots corresponds to one rule, and each column of plots corresponds to either an input variable (yellow, on the left) or an output variable (blue, on the right). It can change the system input either by typing a specific value into the Input window or by moving the long yellow index lines that go down each input variable's column of plots.

Fig.14 Shows the Surface Viewer of Input and Output Membership function

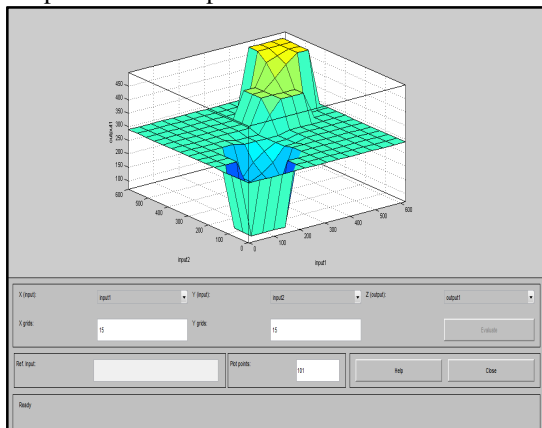


Figure 13Surface Viewer of Input and Output Membership function

The Surface Viewer invoked using surfview('a') is a GUI tool that lets it examine the output surface of a FIS, a.fis, for any one or two inputs. Since it does not alter the fuzzy system or its associated FIS matrix in any way, it is a read-only editor. Using the pop-up menus, it select the two input variables you want assigned to the two input axes (X and Y), as well the output variable it want assigned to the output (or Z) axis. Select the Evaluate button to perform the calculation and plot the output surface. By clicking on the plot axes and dragging the mouse, it can actually manipulate the surface so that it can view it from different angles. If there are

more than two inputs to their system, it must supply, in the reference input section, the constant values associated with any unspecified inputs.

8. CONCLUSION

FL offers several unique features that make it a particularly good choice for many control problems.

➤ It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.

➤ Since the FL controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.

➤ FL is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate-of-change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.

➤ Because of the rule-based operation, any reasonable number of inputs can be processed (1-8 or more) and numerous outputs (1-4 or more) generated, although defining the rule base quickly becomes complex if too many inputs and outputs are chosen for a single implementation since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller FL controllers distributed on the system, each with more limited responsibilities.

➤ FL can control nonlinear systems that would be difficult or impossible to model mathematically. This opens doors for control systems that would normally be deemed unfeasible for automation.

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