Application of Fuzzy Logic in an Optimal PWM Based Control Scheme for a Multilevel Inverter

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Abstract—**Various circuit topologies and control techniques have been proposed on inverters for AC power supply applications but without much emphasis on very high power systems. Incorporation of a non conventional inverter topology known as multilevel inverter with an optimal PWM based control scheme is proposed in this work for high voltage applications when the switching frequency of the inverter power devices is limited by the maximal power loss. A Fuzzy Proportional Integral Controller (FPIC) takes a role in the control scheme in providing stronger control action for a large voltage error and a smoother control action for a small voltage error in the multilevel inverter output. This in turn ensures that high quality output voltage at a fixed frequency is always maintained on the inverter output while the transient response improved regardless of the loading conditions. This paper focus on the development of this control scheme which is supported by some results based on a simulation study.**

Keywords—**Fuzzy logic, multilevel inverter, optimal PWM**

I. INTRODUCTION

An inverter topology for high voltage high power applications that seems to be gaining interest lately is the multilevel inverter. The main feature of a multilevel inverter is its ability to reduce the voltage stress on each power device due to the utilization of multiple levels on the DC bus. This is especially important when a high DC bus voltage is imposed by an application. There are several types of multilevel inverters but the one considered in this work is the modular structured multilevel inverter (MSMI). Unlike other types of multilevel inverters, the MSMI consists of simple single-phase H-bridge inverter modules that are connected in series as a powerful way to build voltage waveforms characterised by any number of levels. The structure of the MSMI is not only simple and modular but also requires the least number of components. It must be realised however that an important requirement of the MSMI is DC sources that are isolated from one another. Thus, the MSMI topology is very much suitable for high power AC power supply applications particularly in power conditioning systems for alternate/renewable sources of energy such as PV arrays and fuel cells due to the originally isolated DC voltages that are available from these sources. The general requirement of inverter systems for high power AC power supply applications is to maintain high quality output voltage with total harmonic distortion (THD) typically specified to be less than 5% at a fixed frequency regardless of the loading conditions. For very high power applications Insulated Gate Commutated Thyristors (IGCT) are recently being used due to its large voltage blocking capability. However, it is a well known fact that the switching capability of thyristor based devices is limited at higher frequencies. This calls for a low switching frequency modulator such as the optimal PWM switching strategy with performance criterion that specifically eliminates the lower order harmonics of the MSMI output voltage. The optimal PWM switching strategy is known to have good steady-state characteristics. However, with most of today's load being non-linear and subject to variations, a feedback control of Fuzzy Proportional Integral Controller (FPIC) is proposed to control the input of the optimal PWM switching angles generator by providing suitable amplitude of the fundamental of the MSMI output voltage in per unit (ap1), depending on the loading conditions.

Fuzzy Logic (FL) control are known to be non-linear and adaptive in nature which gives it faster and more robust performance under parameter variations and load disturbances. This is in line with the basis of FL itself that actually translates the knowledge and experience of the designer of a particular system into the control law. In general, the primary use of switches that are non-linear and time-varying in nature in power electronics converter contributes to difficulty in modeling the system. But with FL, the mathematical model of the system may not be a requirement. Instead, with proper FL design and analysis, a high performance FL controller can be developed for a power converter.

In a previous work, a control scheme was developed for a single-phase MSMI that consists of an online optimal PWM switching angles generator and a Proportional Integral (PI) controller [1]–[3]. The control scheme shows passable performance in fulfilling the general requirements of the MSMI for AC power supply applications such as regulated output voltage at a fixed frequency, good transient response for both loading and unloading conditions as well as low total harmonic distortion. A PI controller however is known to be very sensitive to perturbations and to variations of a system's parameters. Thus, to enhance its performance, modifications such as using a model reference adaptive controller to cancel the effects of the parameter variations or using an auxiliary controller to cancel the effects of the perturbations have to be introduced [4]. In both of these cases, a precise mathematical model of the system is required.

In this work, a feedback control of FPIC is proposed to replace the conventional linear PI controller employed in the previous MSMI system. A fine-tuned FPIC that is based on intuitive experiences and qualitative information on the system is designed to provide suitable ap1 values to the online optimal PWM switching angles generator in fulfilling the requirement of the MSMI for AC power supply applications. Since the FPIC is not designed based on the mathematical analysis of a process model, the design of the FPIC is verified by simulation-based analysis using Matlab's Simulink and Fuzzy Logic Toolbox

II. THE FPIC BASED CONTROL SYSTEM FOR THE MSMI

Fig. 1 shows the basic description of the FPIC based control scheme for the MSMI.

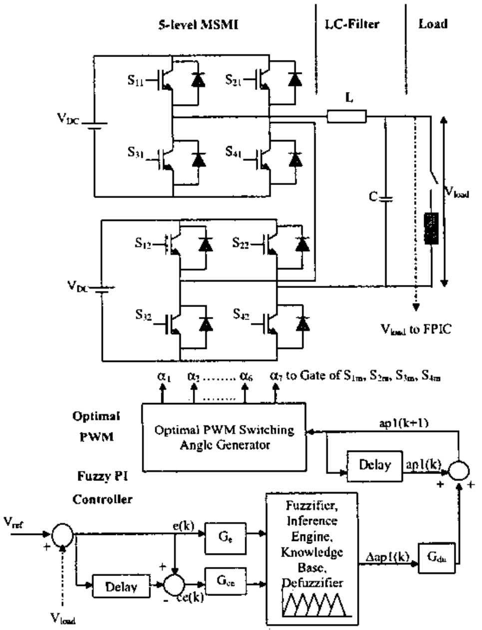


Fig. 1. Proposed FPIC based control system for the MSMI

The actual instantaneous load voltage is sensed, sampled and converted into a root-mean-square (RMS) value before being compared to the RMS value of a sinusoidal reference voltage to yield the error voltage. The RMS voltage as a constant value is more favorable since the controller can easily compensate with the error during steady-state if compared to the periodic sinusoidal voltage which has different instantaneous values for each cycle. The normalized error voltage e(k) and its change of error ce(k) are then processed by the FPIC through fuzzification, fuzzy inference and defuzzification operations. The change in control signal, du(k+1) or Δap(k+1) as the output variables of the FPIC is denormalized and added to the control signal u(k) or ap1(k) to give an updated value of ap1(k+1) or u(k+1) in order to compensate suitably with any loading conditions. The range of ap1 is constrained to vary between 0 and 1 in accordance to the input requirement of the online optimal PWM switching angle generator. The resulting ap(k+1) is then fed into the optimal PWM switching angle generator to energize the power switches appropriately in order to regulate the MSMI output voltage.

To visualize how the system works, the following case is given. Lets say, the instantaneous load voltage suddenly droops from the reference voltage in an increasing rate (i.e. e and ce are positive), then the change of control signal Δap1(k+1) is increased in order to generate the corresponding switching angles. The switching angle generator would then calculate the optimal PWM switching angles based on the online optimal PWM multilevel control strategy for each power device in the MSMI. The filtered MSMI output voltage would therefore be increased to give the desired instantaneous sinusoidal voltage. This repetitive compensation is applied until the error between the waveform of the MSMI output voltage and the reference voltage is reduced or eliminated. Thus, specifications such as percentage of THD below 5% can be maintained and the filtered output voltage can be regulated.

III. THE FPIC DESIGN

A. Design Tools

The most widely used method of testing a fuzzy controller design is by simulation. In this work, MATLAB's Fuzzy Logic Toolbox [4] is used for solving the fuzzy system design, analysis and simulation in an integrated environment. This toolbox can simulate in various states such as transient state response and steady-state error, corresponding to each control goal. It allows creation and editing of fuzzy inference systems in this case, using an interactive graphical tool, Simulink. By accessing to Simulink, a fuzzy system can be tested in a block diagram simulation environment. Different combinations of inputs can easily be tested to observe the corresponding output. The obtained control surface can be analyzed to conform to the expected result.

B. Design Procedures

Fig. 2 shows the flow of the typical design procedures [5] used to develop an FPIC, in this case to provide the gating signal generator with appropriate ap1 values that ensures the sampled MSMI instantaneous load voltage follows the sinusoidal reference waveform. The simulation and testing are conducted several times until a satisfactory result is accomplished. The results are refined by parameter tunings that are based on intuitive experiences and the qualitative results obtained from time to time. Different combinations of input/output scaling factors, shape or location of input and output membership functions (MFs) are possible to obtain the optimal corresponding output during this stage.

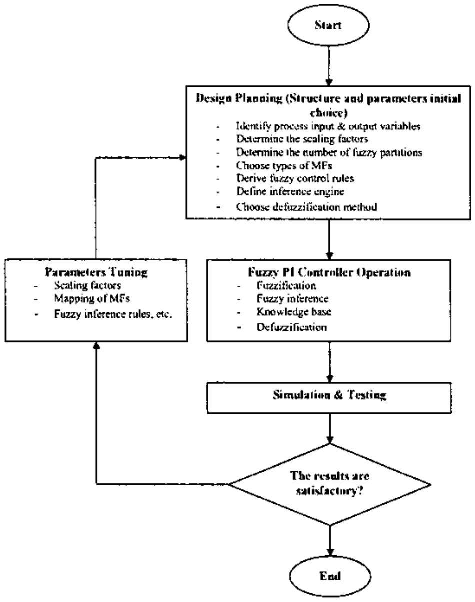


Fig. 2. A typical FPIC design procedures

C. Determining the Scaling Factors

Similar to a conventional control system, the process input and output variable as well as controller input and output variables are firstly determined in the design of the FPIC. In this case, the process is referred to as the 5-level MSMI system with optimal PWM switching angles generator. Therefore the process input is ap1 and the process output is the filtered MSMI output voltage. The FPIC inputs are the error and change of error signals while the output is the change of control signal, Δap1. The scaling factors consist of the normalization gains for the controller inputs (G_e and G_{ce}) and the denormalization gain (G_{du}) for the controller output. The scaling factor is a kind of proportional gain for the forward-path transfer function that is adjusted through experiments as a constant value, to soften the fuzzy logic compensation between two extreme limits. [6] They are initially chosen to satisfy the operational range (the universe of discourse) which is between −1 to +1 for each variable. Generally, with the RMS value of $140/\sqrt{2}$ as the reference signal, the initial value of the normalization gain for the error signal, G_e is,

$$G_e = \frac{1}{140/\sqrt{2}} \qquad (1)$$

The effect of the gain settings for a conventional PI controller in a close-loop system is related to the scaling factors adjustment in the FPIC as it can be approximated as a virtual PI controller. Referring to the conventional PI controller,

$$\Delta u(k) = K_p \Delta e(k) + K_I e(k) \qquad (2)$$

Referring to the fuzzy controller,

$$\Delta u(k) = \frac{G_{ce}}{G_{du}} \Delta e(k) + \frac{G_e}{G_{du}} e(k) \qquad (3)$$

Relating (2) and (3),

$$K_P \equiv \frac{G_{ce}}{G_{du}} \quad \text{and} \quad K_I \equiv \frac{G_e}{G_{du}} \qquad (4)$$

The following conclusions can thus be drawn:

- Increasing/decreasing the G_{du} causes decreasing/increasing K_I and K_P.
- Increasing/decreasing the G_e causes increasing/decreasing K_I.
- Increasing/decreasing the G_{ce} causes increasing/decreasing K_P.

The relationship between both controllers provides similar general references for heuristic tuning of the scaling factors of the fuzzy controller in the manner identical to a conventional PI controller as summarized in Table 1.

TABLE I
EFFECTS OF SCALING FACTORS VARIATIONS

	System response	Increment in gain		
		G_e	G_{ce}	G_{du}
Effect on response	Rise time	Decreased	Decreased	Decreased
	Overshoot/ Oscillation	Increased	Decreased	Increased
	Settling time	Increased	Decreased	Increased
	Steady-state error	Decreased	Increased	Increased

Unlike the conventional PI controller, local adjustment on control surface is possible for the FPIC. In conjunction with the tuning, the controller inputs and output are always monitored to ensure that the controller operates in the defined range.

D. Determining the MFs

In this work, each universe of discourse for two inputs and an output is divided into seven fuzzy subsets that consists of Negative Big (PB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The MFs chosen are the classical triangular shape with 50% overlap. The partition of fuzzy subsets and the shapes of MFs are shown in Fig. 3.

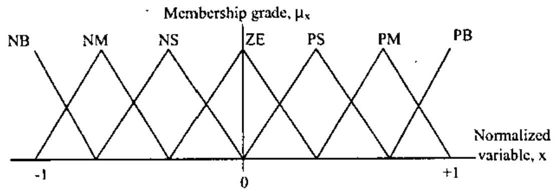


Fig. 3. Triangular shaped MFs

E. Determining the Fuzzy Control Rules

A set of 49 rules is proposed to pass the ap1(k+1) value to the optimal PWM angles generator. Each rule has an intuitive interpretation. The rule base (RB) is derived based on the characteristic of the RMS value of the output voltage signal that is similar with the response for a second order system by applying a step input. Referring to Fig. 4, if the RMS value of the load voltage is less than the RMS value of the reference voltage at point a, then the error signal is positive (P) and the change in error signal is zero (ZE). Consequently, the control action has to be increased, thus giving positive du to enable the load voltage to reach the set point. The combinations of inputs and control action are as summarized in Table 2 [5]. The degree of the control action depends on the value of deviation, for instance, if the error signal is positive big (PB) and the change in error signal is zero (ZE), then the change in control action, du would be positive big (PB).

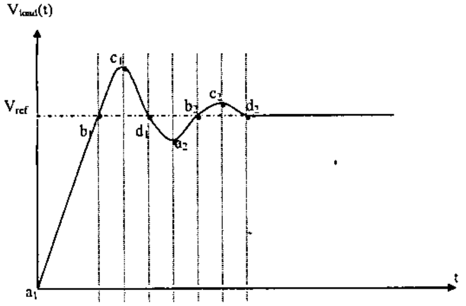


Fig. 4. Response of a second order system

TABLE 3
GENERAL GUIDELINES FOR FUZZY CONTROL RULES DERIVATION

Reference Points	e	ce	du	Notation
a_1, a_2	P	ZE	P	(P, ZE; P)
b_1, b_2	ZE	P	P	(ZE, P; P)
c_1, c_2	N	ZE	N	(N, ZE; N)
d_1, d_2	ZE	N	N	(ZE, N; N)

The final-tuned RB for the FPIC is shown in Table 4.

TABLE 4
RB FOR THE FPIC

		Change of error, ce						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
Error, e	**NB**	NB	NB	NM	NM	NS	NS	ZE
	NM	NB	NM	NM	NS	NS	ZE	PS
	NS	NM	NM	NS	NS	ZE	PS	PS
	ZE	NM	NS	NS	ZE	PS	PS	PM
	PS	NS	NS	ZE	PS	PS	PM	PM
	PM	NS	ZE	PS	PS	PM	PM	PB
	PB	ZE	PS	PS	PM	PM	PB	PB

Usually, RB is the first parameter to be tuned if the result is totally unmatched with the control objective because it may be due to the wrong sign in the output or inputs. Increasing the number of rules provides finer possible adjustment of the control surface. However, minimization of the RB with acceptable system response is essential when considering the practical implementation of the FPIC. The three-dimensional control surface for the derived RB is shown in Fig. 5.

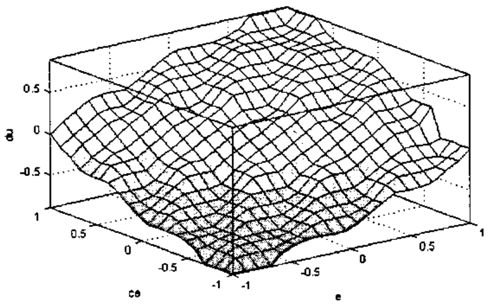


Fig. 5. 3D Control surface for the FPIC

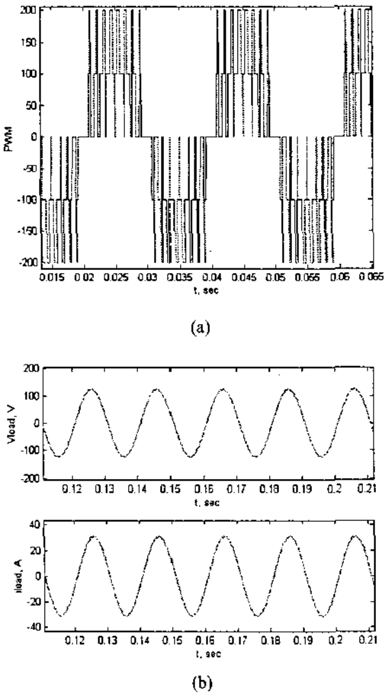
F. Inference Method and Defuzzification Technique

The inference method of Mamdani's max-min composition is chosen in the work to simplify the programming algorithm. Moreover, as tested in the simulation, the choice of Mamdani's max-min composition or Larsen's max-product composition does not give much difference based on the results obtained. The minimum membership value for the antecedents in every k^{th} fired rule propagates through to the consequent and truncates the MF for the corresponding consequent using MIN-operator. Then the truncated MFs for each rule are aggregated using the MAX-operator. The centroid calculation defuzzification method that determines an output (du*) by summing all of the applicable output variables over their relative membership value (weighted average) is selected as the defuzzification method again, due to programming simplicity.

IV. SIMULATION RESULTS AND ANALYSIS

A simulation study is conducted on the MSMI operation that employs the FPIC based control scheme. A sampling interval of 10μsec is chosen in the simulation study because larger sampling interval may affect the performance of the online optimal PWM switching angle generator in terms of missing pulses particularly for lower ap1 values where by pulse widths at a higher frequency exist. For comparison purposes both the open-loop and close-loop operations of the MSMI are simulated. In the MSMI open-loop operation, the simulation is conducted only for ap1 = 0.7. The value of ap1 is chosen as 0.7 since the 5-level characteristic in the MSMI only exists if ap1 is greater than 0.5 and less than 1.

The MSMI output voltage PWM waveform based on the online optimal PWM multilevel control strategy is shown in Fig. 6(a). The waveforms of the filtered MSMI output voltage and load current at rated load are shown in Fig. 6(b). The peak of the fundamental component of the MSMI load voltage (V_{load1} (peak)) and its %THD under both rated and no-load conditions are given in Table 5. From Table 5, the tabulated MSMI load voltage is deviated about ±10% from the desired regulation even though both the %THD at rated load and no-load are within the acceptable limit.



(a)

(b)

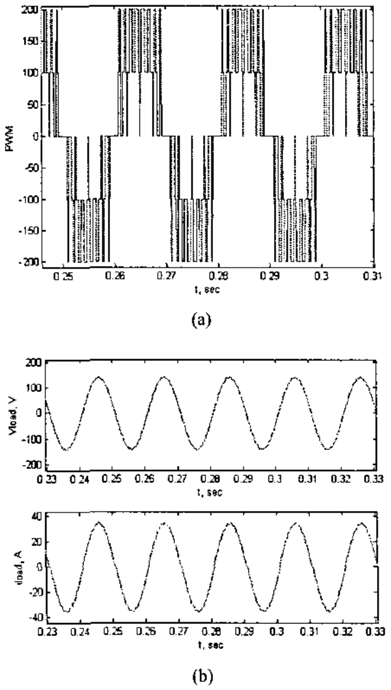
Fig. 6. (a) Output voltage PWM waveform (b) Load voltage (V_{load}) and load current (I_{load}) waveforms for the 5-level MSMI during open-loop operation at the rated load condition for ap1=0.7

TABLE 5

SIMULATION RESULTS OF THE 5-LEVEL MSMI DURING OPEN-LOOP OPERATION AT RATED LOAD FOR ap1=0.7

	Simulation	
	Rated Load (4Ω)	No-load (2kΩ)
V_{load1}(peak) (V)	123.444	154.325
%THD	1.845	1.547

Fig. 7 shows the output voltage PWM waveform and the steady-state responses of the load voltage and current waveforms of the MSMI during the close-loop operation. The peak of the fundamental component of the MSMI load voltage and its corresponding %THD are given in Table 6. The regulation of the load voltage is much more satisfactory with the close-loop operation if compared to the previous results from the open-loop operation. In addition, the %THD is also slightly reduced during the close-loop operation. Thus it can be inferred that although the proposed FPIC is not developed based on a well-known plant model, the MSMI load voltage can still be controlled in terms of regulating it to the specified value of 140 V (V_{load1} (peak)).



(a)

(b)

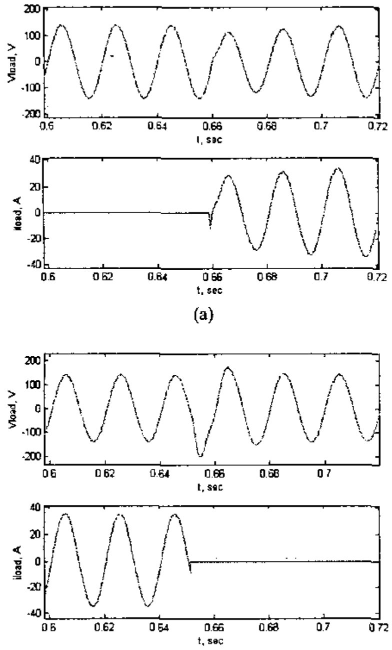
Fig. 7. (a) Output voltage PWM waveform (b) Load voltage (V_{load}) and load current (I_{load}) waveforms forthe 5-level MSMI during close-loop steady-state operation at the rated load condition

TABLE 6

SIMULATION RESULTS OF 5-LEVEL MSMI DURING THE CLOSE-LOOP OPERATION

	Simulation	
	Rated Load (4Ω)	No-load ($2k\Omega$)
V_{load1}(peak) (V)	139.976	139.986
%THD	1.848	1.427
ap1	0.7931	0.6350

The behavior of the MSMI control scheme under various ranges of resistive load step change is also studied. The waveforms of the MSMI load voltage and load current under loading and unloading conditions for the resistive load range of 4Ω to $2k\Omega$ and vice versa are shown in Fig. 8. During the loading and unloading conditions, the load voltage exhibits a high %THD of 16.09 for the step-up resistive load change and 23.93 for the step-down resistive load change. According to the waveforms shown in Fig. 8, the loading condition exhibits a more critical effect if compared to the unloading condition. The load voltage waveform takes about two cycles to remove the effect of disturbance by step-up loading while the step-down loading only takes about one cycle to remove the effect of disturbance.



(a)

(b)

Fig. 8. Load voltage (V_{load}) and load current (I_{load}) waveforms of the 5-level MSMI during (a) loading (b) unloading condition

V. CONCLUSION

A control scheme for the control of an MSMI output voltage particularly for AC power supply applications that is based on an FPIC and an optimal PWM switching strategy has been presented. Without a detailed mathematical model, an FPIC is proven to cope well with the loading and unloading conditions as shown in the close-loop simulation results. The simulation results have also shown that with the FPIC, the filtered MSMI output voltage is regulated at a value very close to 140 V with a THD of less than 5%.

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