Development of a DSP-based Fuzzy PI Controller for an Online Optimal PWM Control Scheme for a Multilevel Inverter

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***Abstract*—Previous work has presented the incorporation of a non conventional inverter topology known as multilevel inverter with an optimal PWM based control scheme for high voltage AC power supply applications. 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 focuses mainly on the FPIC and its implementation using a digital signal processor (DSP) as part of the hardware implementation of the control scheme. A test conducted on the DSP-based FPIC operation shows response that is in good agreement to that obtained from a simulation study conducted using MATLAB/Simulink.**

Keywords- multilevel inverter, Fuzzy PI, DSP, optimal PWM

I. INTRODUCTION

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 Modular Structured Multilevel Inverter (MSMI) with an online optimal PWM control scheme has been proposed in [1]-[3] 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. Results that show the performance of the control scheme 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 have also been presented. The results however are based on a simulation study conducted using MATLAB/Simulink.

This paper presents the development of the FPIC as part of the hardware implementation of the proposed online optimal PWM control scheme for the MSMI using Texas Instruments TMS320C31 digital signal processor (DSP). For continuity purposes, the following section describe briefly the basic principle of the of the FPIC-based online optimal PWM control scheme proposed earlier [4],[5]. This is followed by the proposed hardware implementation of the control scheme and its achievement thus far. The results obtained from the DSP implementation of the FPIC are compared with that from the simulation study for evaluation purposes. Some analysis on the results obtained and issues related to the DSP-based FPIC are also given followed by the conclusion.

II. THE FPIC-BASED ONLINE OPTIMAL PWM CONTROL SCHEME

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 as mentioned in the previous section. 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 [6]. In both of these cases, a precise mathematical model of the system is required.

In [4] and [5], a feedback control of an FPIC is proposed to replace the conventional linear PI controller employed in the online optimal PWM control scheme presented in [1]-[3]. A fine-tuned FPIC that is based on intuitive experiences and qualitative information on the system is designed to provide suitable amplitude of the fundamental of the MSMI output voltage in per unit values, ap1 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. Fig. 1 shows the basic description of the FPIC based online optimal PWM control scheme 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 favourable 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. Details of the FPIC design have been described extensively in [4 and [5].

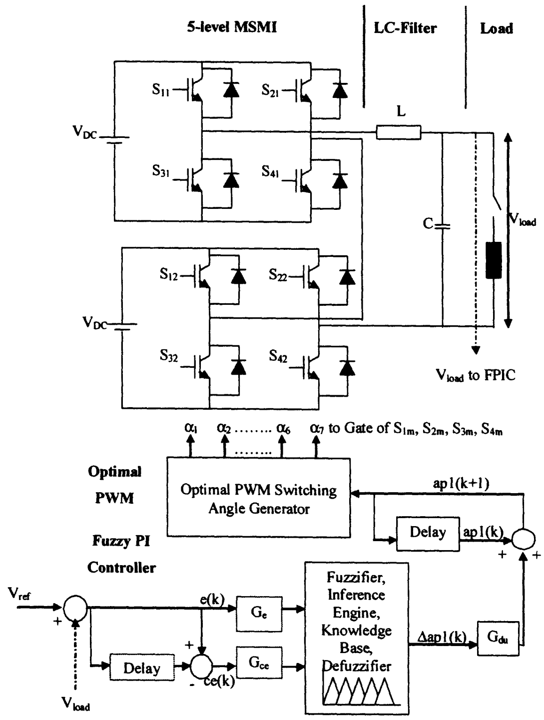

Fig. 1. Proposed FPIC-based online optimal PWM control scheme for the MSMI

III. Proposed Hardware Implementation

The performance of the FPIC-based online optimal PWM control scheme has been evaluated in [4] and [5] based on the results of a simulation study. The results have highlighted the capability of the control scheme in regulating the MSMI load voltage at a specified value with a Total Harmonic Distortion (THD) of less than 5% during steady state conditions. In addition, the control scheme has also been proven to cope well with loading and unloading conditions. The THD of the MSMI load voltage at the point of loading or unloading is more than 5% but the effect of these disturbances only last for at most two cycles before it drops to an acceptable level [4]. Finally, with a greater range of the resistive load change, a higher %THD but still below 2% is observed during steady state conditions [5].

To verify the performance of the FPIC-based online optimal PWM control scheme for the MSMI, its hardware prototype is planned for development. The proposed hardware implementation of the whole control scheme is through the use of a DS1102 controller board. This controller board is based on the Texas Instruments TMS320C31 floating-point DSP, which builds the main processing unit, providing fast instruction cycle time for numeric intensive algorithm [7]. The board interfaces to the host, which in this case is a personal computer, via a standard PC/AT interface bus.

Using the DS1102 board, the control scheme implementation is expected to be simple and compact as it is based on the DSP only without any additional component requirement. With the DS1102 controller board, equations related to both the FPIC and the online optimal PWM switching angle generator can be applied to the DSP through the development of C-language programs. As the online optimal PWM switching angle generator has already been implemented on the DS1102 controller board [1]-[3], the main task of the work is to develop the FPIC separate from it in order to minimize the complexity of the C-language program. Future work however may incorporate the DSP-based FPIC with the online optimal PWM switching angles generator to complete the hardware implementation of the proposed control scheme.

IV. Development Of The Dsp-based Fpic

Referring to Fig. 1, a voltage transducer will be typically used to sense the actual MSMI instantaneous load voltage, before sending it to the Analogue to Digital Converter (ADC) on the DS1102 controller board. At every sampling interval, the instantaneous RMS values of the sinusoidal reference voltage and load voltage are used to calculate the error, e and change of error, ce signals that act as the inputs to the FPIC. The stage of fuzzification, fuzzy inference and defuzzification are then performed accordingly in the C-language program as generally described in the flowchart of Fig. 2.

In the program, each of the membership function is defined by representing it in three points notation since it is chosen to be triangular-shaped [4],[5]. These three points are then used in calculating two linear equations that represent each fuzzy subset during the fuzzification stage. The rule base of 49 rules

[4],[5] is coded in order to perform loop calculations for the MAX-MIN operation in the fuzzy inference stage. In the defuzzification stage, if the final output which is ap1 is greater than 1, then the limiter in the program sets the ap1 to 1 while if the output is less than 0, then the ap1 is set to be 0. This operation is repeated at every sampling interval. The steady-state value of ap1 can then be observed clearly and the cycle is repeated after resetting the parameters. In a complete control system, the ap1 values will become the input to the optimal PWM switching angles generator that eventually generates the gating signals for each of the MSMI power devices.

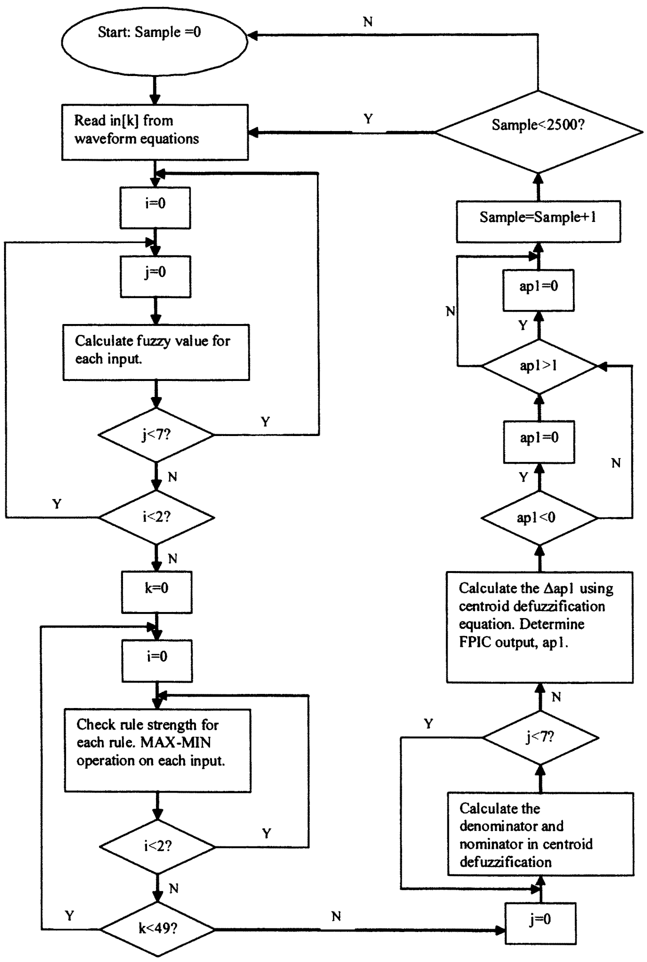

Fig. 2. Flow chart of the DSP-based FPIC

V. RESULTS AND ANALYSIS

Initial results from the implementation of the FPIC on the DS1102 controller board has shown that based on the developed C-language program, the achievable sampling interval is only 400 μsec. This sampling interval is considered to be large as it actually relates to a resolution of 7.2° for the MSMI gating signals. If both the FPIC and online optimal PWM switching angles generator were to be incorporated, it is expected that the sampling interval achievable will be higher. This would contribute to missing pulses in the gating signals particularly when pulse widths that are less than one sampling interval exist. Thus before further improvement is made to reduce the achievable sampling time, a different approach is taken to test the feasibility of the developed DSP-based FPIC.

A closed-loop operation of the FPIC in the MSMI control scheme is firstly simulated at a sampling interval of 400μsec for 1 second with suitable tuned gain settings. This relates to 2500 sampling intervals as shown in Fig. 2. Then, the signal profiles of the RMS values of the sinusoidal reference voltage and load voltage obtained from the simulation study are transformed into numbers of linear equation in order to get the approximated signal profiles that can be used to test the DSP-based FPIC operation. The FPIC operates based on the calculations of e and ce from the two signal profiles and consequently generates the corresponding control action, in this case the value of ap1 as the input to the online optimal PWM switching angles generator. The signals of the FPIC inputs (normalized e and ce) and output (ap1) from the simulated and DSP-based FPIC are as shown in Fig. 3, Fig. 4 and Fig. 5.

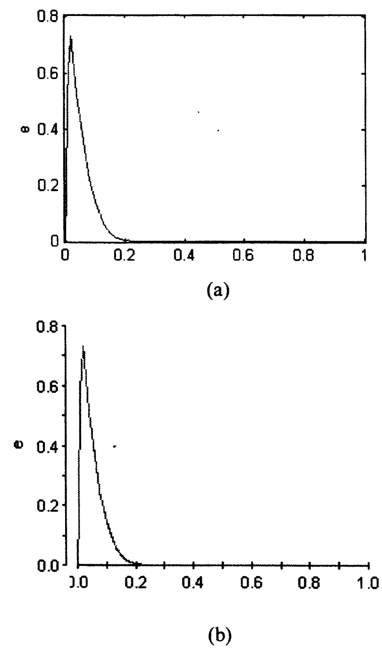

Fig. 3. The waveforms of normalized error (e) from (a) Simulation (b) DSP

The steady-state ap1 value obtained from the DSP-based FPIC (0.7679) is found to be in good agreement to that obtained from the simulated FPIC (0.7683) as can be depicted from Fig. 5. It can be noted from Fig. 2 that the ce signal from the DSP presents some spikes in contrast to the rather smooth signal of its simulated counterpart. The e and ap1 signals from the DSP also generate almost identical signals to that obtained from the simulation study. All three signals are found to remain within the range as defined in the FPIC, which is −1.0 to +1.0. The response of the designed FPIC in generating proper ap1 values can also be considered fast with it reaching steady-state within around 0.2 seconds from the starting of the operation after the e and ce signals are eliminated due to the feedback control action of the controller.

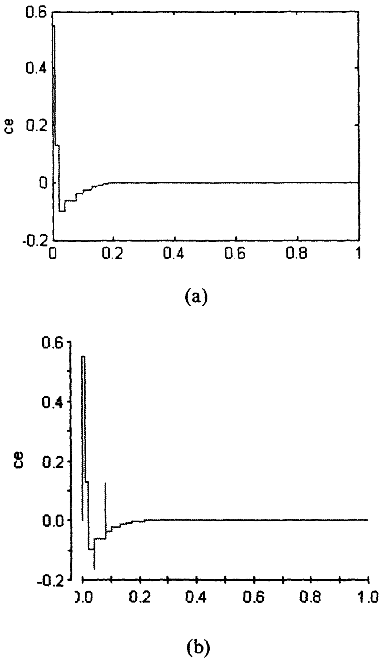

Fig. 4. The waveforms of normalized change of error (ce) from (a) Simulation (b) DSP

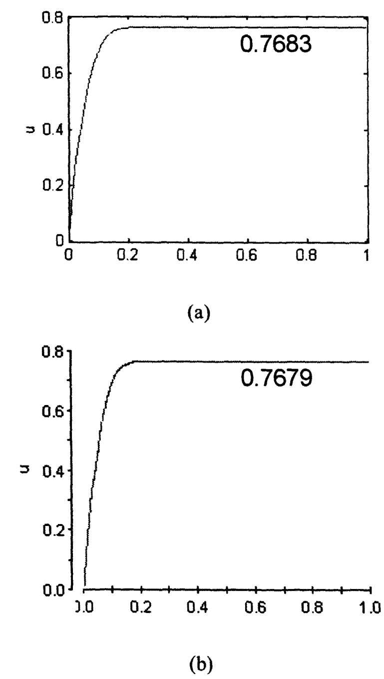

Fig. 5. The waveforms of ap1 from (a) Simulation (b) DSP

VI. Issues Related To Hardware Implementation Of The Control Scheme

Various factors may contribute to the large sampling interval achieved by the DS1102 controller board in implementing the FPIC. Firstly, it must be noted that the number of rules in the FPIC design is 49 which can be considered as large. In [8] for example, the handling of 11 rules required 400 µsec sampling interval as well using a TMS320C14 DSP with a feature of 200 nsec single cycle instruction execution time. The TMS320C31 however has a better feature of 33.33 nsec single cycle instruction execution time but in this case deals with about 4 times larger number of rules. If a simple and compact hardware implementation of the control scheme is to be maintained, one alternative is to switch to new DSPs with much faster execution times. Such DSP may be able to execute the tasks associated with the FPIC and the online optimal PWM switching angles generator within reasonable sampling interval that can ensure the accuracy of the gate signals generated.

Another point to consider is the designed algorithm of the FPIC in the C-language program itself. The program may require further optimisation in terms of the approach taken in designing the algorithm of the FPIC so that a smaller sampling interval can be achieved. In [9] for instance, a table look-up approach was taken to implement a fuzzy controller. In this case the DSP only calculated the e and ce signals while the control action was obtained directly from a look-up table. Such approach however required offline computation of the fuzzy decision table which was then stored in the flash EEPROM of a DSP.

VII. Conclusions

The development and performance analysis of a DSP-based FPIC for an online optimal PWM control scheme for an MSMI has been presented. The results have shown that the performance of the DSP-based FPIC is in good agreement to that based on the simulation studies using MATLAB's Fuzzy Logic Toolbox. The high sampling interval achievable by the DSP in generating its output however indicates that further improvement has to be made to the current FPIC C-language program algorithm for the DS1102 controller board. This is vital in order to accommodate for its future incorporation with the online optimal PWM switching angles generator that demands for the smallest possible sampling interval to ensure accuracy in the gate signals generation.

References

[1] N. A. Azli and A. H. M. Yatim, "Modular Structured Multilevel Inverter (MSMI) for High Power AC Power Supply Application", *Proc of the IEEE International Symposium on Industrial Electronics ISIE' 01,* Vol. 2, pp. 728-733, 2001.

[2] N. Ahmad Azli and A. H. Mohd Yatim, "A DSP-based Online Optimal Pulse Width Modulation (PWM) Switching Strategies for a Modular Structured Multilevel Inverter" , *Proc. of the 6th International Symposium*

on Signal Processing and its Applications ISSPA '01, Vol. 2, pp. 623-626, 2001.
[3] N. A. Azli. and A. H. M. Yatim, "Optimal Pulsewidth Modulation (PWM) Online Control of a Modular Structured Multilevel Inverter (MSMI)" ,*The 4th IEEE International Conference on Power Electronics and Drive Systems PEDS'01*, Vol. 2, pp. 598-604, 2001.
[4] N. A. Azli and W. S. Ning "Application of Fuzzy Logic in an Optimal PWM Based Control Scheme for a Multilevel Inverter." *2003 International Conference on Power Electronics and Drive Systems PED 2003,* Singapore, 17-20 November 2003.
[5] N. A. Azli and W. S. Ning ," Application of Fuzzy Logic in Regulating a Multilevel Inverter Output", *Proceedings of 2004 International Conference on Power System Technology,* Singapore, 21-24 November 2004.
[6] *Fuzzy Logic Toolbox User's Guide*, The Math Works, Natick, MA, 1996, pp. 1–6.
[7] *Floating-Point Controller Board: DS1102 User's Guide*, dSPACE Gmbh.,Germany 1996.
[8] *Fuzzy Logic: An Overview of the Latest Control Methodology-Application Report,* Texas Instruments, pp. 10-18, 1993.
[9] J. Li, K. Yong and J. Chen, "Fuzzy-Tuning PID Control of an Inverter with Rectifier-Type Nonlinear Loads", *Proc of the 3rd International Power Electronics and Motion Control Conference PIEMC*, pp. 381-384, 2000.