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Selecting appropriate fuzzy PID control structure for power electronic applications

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Abstract: A comprehensive library of Fuzzy Proportional-Integral-Derivative (PID) controllers for power electronic systems has recently presented in the literature. In this library, the authors derived a 27 Fuzzy PID structures and many hybrid Fuzzy PID controllers. This paper is an extended research for the aforementioned work. Here and as a study case, a switched mode power converter (SMPC) application is considered showing the procedure for selecting the applicable structure from the derived FPID library. Such systems require robust, and highly dynamic performance, control schemes to facilitate optimum and high efficiency performance, often under a wide and challenging range of operating conditions. Here, a fuzzy PD + I (FPD + I) structure is directly selected from the derived FPID library. Simulation analysis and experimental validation on a DSP (TMS-320F28335) controlled prototype synchronous DC-DC buck converter demonstrate the superior dynamic performance and voltage regulation of the selected FPID structure compared to the conventional CPID control scheme.

1 Introduction

It is well-recognised that many power electronic converter applications that rely upon the classical, fixed gain, proportional-integral-derivative (PID) controller deliver sub-optimal dynamic performance [1, 2]. Key issues, which can affect the transient performance of power electronic systems, include component tolerances, device non-linearity, and temperature dependency, unexpected external disturbances, and poor knowledge of the load behaviour [3, 4]. For optimal control performance, advanced and intelligent control algorithms are required. A range of attractive methods have been presented in the literature; non-linear controllers [5], adaptive controllers [6], and fuzzy logic controllers (FLC) [7] have all been effectively applied in mainstream power electronic applications. However, compared to the classical PID controller, many of these methods are less well understood, more difficult to design, and potentially more computationally intensive to implement on microprocessor hardware [8]. In comparison with other control algorithms, FLC is relatively easy to design and implement. In FLC, the system model is not essential in the design process and excellent performance can be achieved when controlling non-linear systems, applications containing high degrees of uncertainty, or systems with unobservable parameters [9]. Such properties are often found in modern power electronic applications; for example, grid impedance variation (uncertainty) in grid-connected renewable energy systems [10].

In the field of power electronic systems, several beneficial FLC structures have been proposed which can be used to replace existing classical PID controllers with more intelligent control algorithms. Examples can be found in [9, 11]. Furthermore, as reported in the literature [9, 12–14], hybrid FLC structures have been effectively applied in many digitally controlled power electronic applications. Hybrid structures typically reduce computational complexity and alleviate hardware implementation concerns [1]. In other research, hybrid Fuzzy PID (FPID) controllers have also been deployed where elements of the conventional PID controller are combined with the FPID controller. This can be realised by adding a conventional proportional, derivative, or integral element in parallel with a fuzzy controller such as FPD, FPI *etc*. This scheme generally offers superior dynamic performance in comparison with conventional PID structures [9, 15]. Reliant upon above-mentioned arguments, the authors in [1] present a comprehensive library of digital Fuzzy PID (FPID) control structures for industrial applications. Unlike many papers, which focus on a single control solution, the work in [1] takes a systematic approach to convert all 27-possible digital conventional PID (CPID) structures to a digital FPID equivalent. A backward Euler rule approach is applied to convert from *s* to *z* domain, rather than the commonly applied direct bilinear transformation. This simplifies the implementation of hybrid FPID structures [1]. However, even with a library of all possible structures, the optimal choice of control structure is not always well understood and correctly applied in many situations. This is particularly true in complex power electronic systems. Moreover, the situation is further complicated by the vast array of possible tuning techniques, all of which have their own advantages and disadvantages.

For this reason, this paper considers the process of selecting the candidate FPID structure from the derived FPID library. As a case study example, the controller design for a DC–DC buck converter switch mode power converter (SMPC) is considered. The performance of the controller is validated experimentally. Such systems are cost-sensitive, require high-performance operation, and the merits of using the proposed FPID library in [1] can readily be appreciated.

2 Procedure for appropriate selection of FPID structures – A case study

2.1 Voltage mode control SMPC – simulation results

This section provides simulation validation for the appropriate selection of an FPID structure for a target application. From a fuzzy logic control point of view, selecting an appropriate control structure based on the heuristic control knowledge of the specified application is preferred. From previous studies, it is found that a hybrid adaptive PD + I control structure is often successfully applied in the control of DC–DC buck converters. Examples are presented in [6, 16]. In [6], an adaptive PD + I based on a prediction finite impulse response (FIR) filter controller is employed to improve the dynamic performance of an SMPC. While in [16], an optimised, self-tuning PD + I controller is proposed. Here, it is proposed to replace the adaptive/self-tuning PD + I controller presented in [6, 16], with a direct equivalent FPD + I controller and demonstrate the improved system performance. As a result, the procedure can be followed in the selection of the

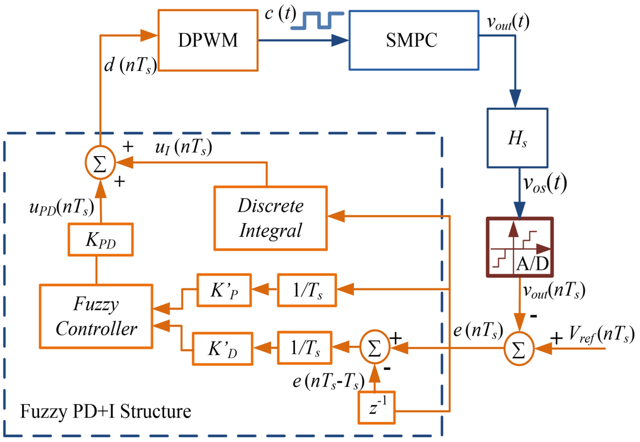

Fig. 1 *Application of Fuzzy PD + I control structure for SMPC*

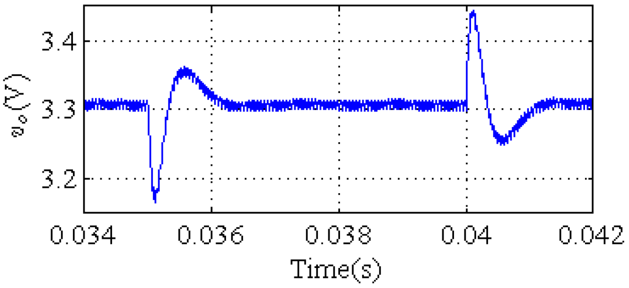

Fig. 2 *Transient response of the CPID controller. Load current change between 0.66 and 1.32 A every 5 ms*

appropriate control structure from the developed FPID library. Therefore, from the FPID library derived in [1], the appropriate FPD + I controller is selected (2). Fig. 1 shows the block diagram of the digitally controlled SMPC, including the selected FPD + I structure. Referring to Fig. 1, (1) shows the FPD controller, while (2) presents the conventional I controller. Finally, (2) represents the control action of the FPD + I.

$$K_{\rm PD}u_{\rm PD}(nT_s) = K'_P\frac{e(nT_s)}{T_s} + K'_D\Delta e(nT_s) \qquad (1)$$

$$d(nT_s) = K_{\rm PD}u_{\rm PD}(nT_s) + u_I(nT_s) \qquad (2)$$

where

$$u_I(nT_s) = K_I{\rm e}(nT_s) + u_I(nT_s - T_s) \qquad (3)$$

Here, K'_P is the proportional gain, K'_D is the derivative gain, $K_{\rm PD}$ is the fuzzy output gain, K_I is the integral gain, d (nTs) is the duty cycle, and T_s is the sampling rate.

In order to compare and validate the performance of the proposed structure (FPD + I), a conventional PID voltage controller is also simulated using MATLAB/SIMULINK. The circuit parameters of the buck converter are as follows [6]: $L = 220$ µH, $C = 330$ µF, $R_o = 5\ \Omega$, $R_L = 68$ mΩ, $R_C = 25$ mΩ, $V_{\rm in} = 10$ V, the switching frequency is $f_{sw} = 20$ kHz, and the sensor gain is $H_s = 0.5$, and the sampling time $T_s = 50$ µs ($f_s = f_{sw}$). A well-known pole-zero cancellation method presented in [17, 18] is utilised to determine the PID gains (*i.e.* q_0, q_1, and q_2). Here, we found: $q_0 = 4.127$, $q_1 = -7.184$, and $q_2 = 3.182$ [6].

$$G_c(z) = \frac{q_0 + q_1z^{-1} + q_2z^{-2}}{1 - z^{-1}} \qquad (4)$$

where q_0, q_1, and q_2 are the gains of the digital controller. Those gains are determined by converting the analogue PID controller to digital PID controller by using pole-zero cancellation technique. This conversation can be simply accomplished by using MATLAB environment.

To examine the transient response of the conventional PID controller, a periodic step change in the load of the buck converter is applied. As a result, a repetitive load current change between 0.66 A and 1.32 A, at 5 ms intervals, is observed, demonstrates the resultant buck converter output voltage, while it is well regulated, it exhibits significant oscillatory behaviour at the point of load change (Fig. 2) [6].

Now, the FPD + I controller in Fig. 1 is also simulated using MATLAB/SIMULINK. For the system under study, the universe of discourse for both $e(nT_s)$ and $\Delta e(nT_s)$ is normalised to be within the scale range of [1–1]. The controller gains (*ie.* K'_D, K'_P, $K_{\rm PD}$) are used to adjust the input and output signal of the fuzzy controller (the universe of discourse sets). For ease of hardware implementation, triangular memberships are adopted for the input and output (except two trapezoidal memberships are utilised at the beginning and at the final of the fuzzy sets) and a centre of gravity method is used in the defuzzification process. The memberships are symmetrical. Note that the duty cycle for the SMPC is limited to be within 10 to 90%. In this work, a Mamdani type fuzzy controller with MIN-MAX compensator is utilised and seven memberships are employed with linguistic variables: Negative Small (NS), Negative Medium (NM), Negative Big (NB), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). In general, the final rule base of the FPD will be developed and optimised by the control engineer. Here, the controller rule base is designed based on the knowledge of the conventional PD behaviour, and from the understanding of the DC–DC converter characteristics (Table 1). For instance, if the output of the SMPC is far away from the desired regulated voltage (error is big), a large control action that pulls the output towards the reference voltage is required. Likewise, only a small amount of control action is required when the regulated output voltage is approaching the steady state (error is small or zero). Hence, the Mamdani approach is very well suited [19]. However, it is worth noting that alternative rule bases are available and may be better suited to alternative applications. Any of these rules are complementary to the FPID controller structures presented here. Importantly, due to the uncertainty and non-linear behaviour of power electronics systems, a non-linear rule should ideally be included in the controller rule base. This will clearly improve the performance of the controlled

Table 1 Rule base for FPD controller

$e(n)/\Delta e(n)$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NM	NB	NS	Z	PS	PM
z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PM	PM	PM
PB	Z	PS	PM	PB	PB	PB	PB

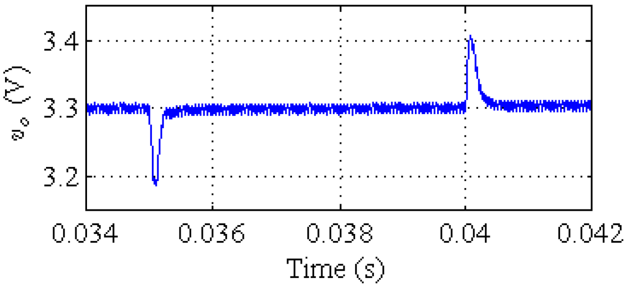

Fig. 3 *Transient performance of the selected FPD + I controller during load current change. a: output inductor L = 100 µH and C = 330 µF, b: C = 660 µF and L = 220 µH*

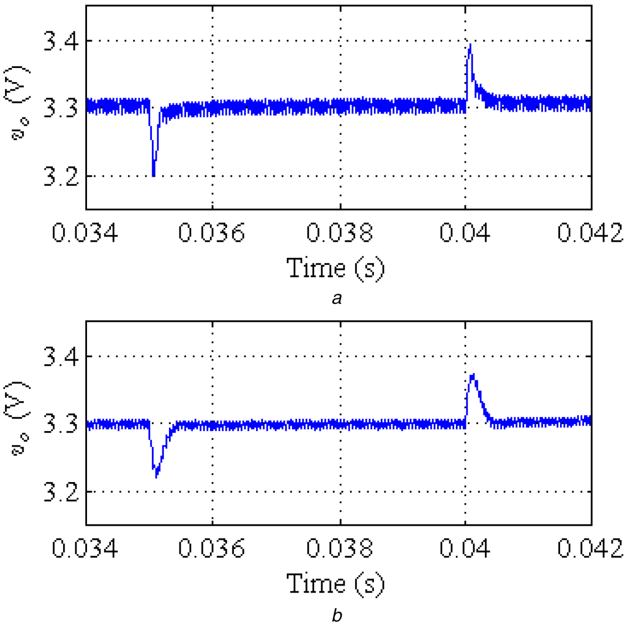

Fig. 4 *Transient performance of the selected FPD + I controller during load current change. a: output inductor L = 100 µH and C = 330 µF, b: C = 660 µF and L = 220 µH*

system. For two inputs-single output fuzzy controllers, the following rule base control expression can be adopted:

$$\text{if } e \text{ is } A \text{ and } \Delta e \text{ is } B \text{ then } u \text{ is } C \qquad (5)$$

where A, B is the input fuzzy sets and C is the output fuzzy sets.

Compared to the conventional PID controller results (Fig. 2), the FPD + I scheme offers significantly improved transient performance (Fig. 3) for the same dynamic load change with lower transient overshoot, less oscillatory behaviour, and faster recovery time. The obtained simulations results confirm the effectiveness of fuzzy control design, as well as it confirms the validity of the selected structure.

The versatility of the selected FPD + I control structure has been tested with other converter circuit parameters. It has been evaluated by changing the output inductor to a lower value (Fig. 4*a*) and by changing the output capacitance with higher values (Fig. 4*b*) from the original design. To study the dynamic behaviour of the system during these changes, a periodic load change is introduced. In each case, the proposed fuzzy structure presents very promising results and can handle a wide range of uncertainty in the SMPC parameters; it approximately provides similar performance to the control scheme in [6].

In comparison with the works presented in [6, 16], the proposed structure (FPD + I) is computationally simpler and more straightforward to implement; in addition, it provides robust performance. In [6], the control design requires a deep knowledge of adaptive signal processing techniques for successful implementation. Furthermore, the adaptive controller may be prone to accumulate learning that prevent the gains to convergence to desired values. In [16], the proposed self-tuning controller takes a long time to tune the parameters of the PID controller. Moreover, an excitation signal must be injected into the control loop which may produce an undesirable, albeit small, disturbance into the regulated output voltage.

2.2 Voltage mode control SMPC – experimental results

To fully validate the proposed control system, a laboratory prototype synchronous DC–DC buck converter has been implemented. For comparison with the simulation results, the same parameters and component values to those outlined in Section 2.1 are chosen (allowing for normal component tolerances). A Texas Instruments TMS320F28335 digital signal processor (DSP) platform is used to implement the selected FPD + I scheme (see Fig. 1). Again, a conventional PID voltage controller is implemented on the experimental hardware. The PID is set to control the buck converter output voltage at 3.3 V [6]. This serves as a test bed for testing the FPD + I controller. The classical PID gains are optimally tuned using the aforementioned pole-zero cancellation techniques (4). The transient characteristics of the PID controller are determined by applying a repetitive step change in load to the buck converter. This step change causes the load current to switch between 0.66 and 1.32 A at 25 ms intervals. The results, shown in Fig. 5 [6], demonstrate that the buck converter is always operating in continuous current mode. The output voltage transient shows significant oscillatory behaviour at the points of load change, and the steady-state recovery time is approximately equal to 2.60 ms. Following this, the FPD + I controller is implemented on the DSP. For consistency, all circuit parameters remain the same, and the buck converter is subjected to the same load change as previously described. Fig. 6 presents the rules surface viewer of the FPD controller (Table 1). A straight forward two-dimensional look-up table technique is used to implement the rules surface viewer on the DSP 7 × 7, rule base. Fig. 7 shows the experimental results of the selected structure FPD + I. Compared to the classical PID controller results (Fig. 5), the FPD + I scheme produces significantly improved transient performance for the same dynamic load change with less oscillatory behaviour and faster recovery time; again similar performance to the control scheme in [6]. Also, importantly, the steady-state recovery time is significantly faster at 1.68 ms.

3 Conclusion

This paper has presented the procedure for selecting an appropriate Fuzzy PID controller from an available library of 27 FPID structures for power electronic applications. A practical example of regulating the output voltage of an SMPC is presented. The

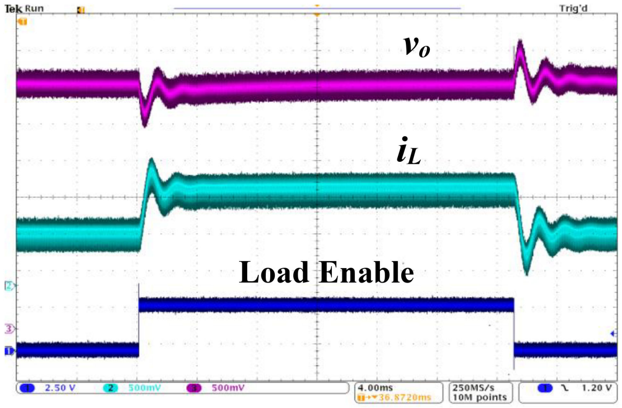

Fig. 5 *Transient response of CPID controller with abrupt load change between 0.66 and 1.32 A. 4 ms/div*

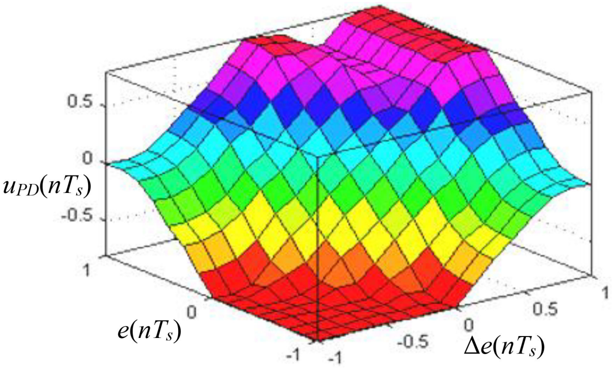

Fig. 6 *Fuzzy PD rule surface viewer*

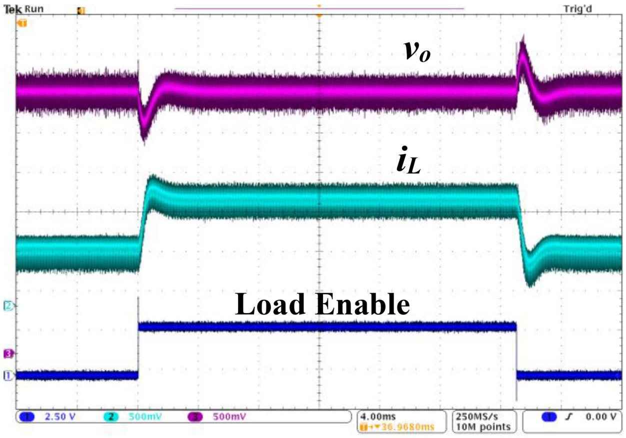

Fig. 7 *Transient response of proposed Fuzzy PD + I structure with abrupt load change between 0.66 and 1.32 A. 4 ms/div*

selection procedure is started by reviewing the effective control structures for the target application and then select the match fuzzy PID structure from the derived FPID library. Simulation and experimental results demonstrate the superior performance of the selected Fuzzy PID controller when compared to a conventional PID controller. A significant reduction in oscillatory behaviour was observed when a step load change is applied to the FPID-controlled SMPC. Furthermore, a 35% improvement in steady-state recovery time is achieved, clearly demonstrating the importance of choosing an appropriate controller structure.

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