Modeling a Fuzzy Logic Controller for Power Converters in EMTP RV

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Abstract - This paper presents the design of an Incremental Fuzzy Gain Scheduling Proportional and Integral Controller (IFGSPIC) for the current control of a rectifier fed power system. The current error and its derivative are used to adapt online the gains of a PI controller according to fuzzy reasoning and fuzzy rules. A Larsen reference engine, center average defuzzification and most natural and unbiased membership functions (MFs) (i.e. symmetrical triangles and trapezoids with equal base and 50% overlap with neighboring membership functions) are used. This simplifies the controller design and reduces computation time under the EMTP RV simulation environment. To improve performance, the IFGSPIC is designed like a hybrid controller with the initial values of the proportional and integral gains of IFGSPIC determined by the Ziegler-Nichols tuning method. This combines the advantages of a fuzzy logic controller and a conventional PI controller. During transient states, the PI gains are adapted by the IFGSPIC to damp out the transient oscillations and reduce settling time. During the steady state, the controller is automatically switched to the conventional PI controller to guarantee system stability and accuracy. Performance evaluation of the two controllers under disturbances and step changes to the setting-point are studied. The performance comparison is made in terms of criteria such as rising time (t_r), percent maximum overshoot (%OS), five percent settling time (t_s), integral of the absolute error (IAE) and integral of the squared error (ISE). Results show that the proposed controller outperforms its conventional counterpart in each case.

Keywords: Fuzzy control, Gain scheduling, EMTP RV

I. INTRODUCTION

Power converters, which are non-linear plants, traditionally use PI controllers to regulate the power transmitted to the required level. Although PI controllers, with fixed values of proportional and integral gains, are simple and robust, their performance can only be optimal at one operating point and prone to instability when systems are nonlinear and have uncertainties. However, with proper scheduling of controller gains according to the system operating conditions, the above problems can be overcome. When using gain scheduling, the abrupt changes to the parameters of the controller can lead to an unsatisfactory or even unstable control performance. However, using fuzzy gain scheduling proposed in [1,2,10,11], it is possible to ensure that the controller parameters change in a smooth fashion. An expert's experience is used to define a set of fuzzy rules that relates the controller parameters to particular operating conditions and fuzzy inference is used to generate the appropriate parameter values for a particular operating point.

The purpose here is to model a fuzzy logic controller for power converters in EMTP RV, which is a circuit-oriented simulator that has been developed specifically for power system modeling. An Incremental Fuzzy Gain Scheduling Proportional and Integral Controller (IFGSPIC) is proposed. A comparative study is used to demonstrate the feasibility and effectiveness of the proposed schemes with the fuzzy PI-like controller and conventional fixed gain PI controllers.

II. FUZZY RULE-BASED SYSTEMS

A fuzzy rule-based system is composed of four components, as shown in Figure 1. Fuzzification is the process of converting a crisp value to a fuzzy point. In this system, fuzzy singletons are used as fuzzifiers.

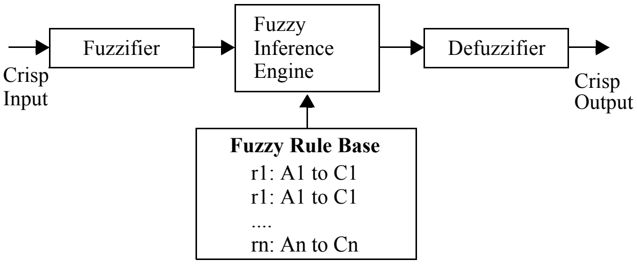

Figure 1: Fuzzy rule-based system

$$m_{A'}(x) = \begin{cases} 1 & if\ x = x' \\ 0 & otherwise \end{cases} \tag{1}$$

where x' is a crisp input value from a process.

The Larsen inference engine is used because it has a simple and efficient computation.

$$m_{R_i}(x, y, z) = m_{A_i}(x) m_{B_i}(y) m_{C_i}(z) \tag{2}$$

where x and y are inputs, and z is output, A, B, C are fuzzy subsets, and μ is a MF.

A center average defuzzifier is used for defuzzification. Finally, a closed form representation of fuzzy system can be achieved as follows:

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$$f(x,y)=\frac{\sum_{i=1}^{n} z_i^{'} m_{A_i}(x) m_{B_i}(y)}{\sum_{i=1}^{n} m_{A_i}(x) m_{B_i}(y)} \qquad (3)$$

When unbiased MFs, i.e. symmetrical triangles and trapezoids with equal base and 50% overlap with neighboring MFs, are used, the following condition can be achieved [2]:

$$f(x,y)=\sum_{i=1}^{n} z^{'} m_{A_i}(x) m_{B_i}(y) \qquad (4)$$

This simplifies the computation for EMTP RV modeling and is the primary reason that Larsen inference engine and center average defuzzifier are chosen here. A set of fuzzy **if-then** rules then construct the fuzzy rule base.

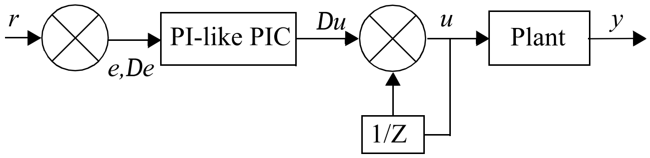

Figure 2: Block diagram of the PI-like FLC system

III. FL CONTROLLER & RULE BASE DESIGN

A. PID-like Fuzzy Logic Controller

If a fuzzy controller is designed to generate the control actions within the proportional-integral-derivative (PID) concepts, it is called a PID-like fuzzy logic controller (FLC). The control signal or the incremental change of control signal is built as a nonlinear function of the error, change of error and acceleration error, where the nonlinear function includes fuzzy reasoning. There are no explicit PID gains; instead the control signal is directly deduced from the knowledge base and fuzzy inference. A block diagram of the general PI-like FLC is shown in Figure 2.

A PI-like FLC has two inputs, the error *e(k)* and change of error *De(k)*, which are defined by *e(k) = r(k) - y(k)*, and *De(k) = e(k) - e(k-1),* where *r* and *y* denote the applied set point input and plant output, respectively. Indexes *k* and *k-1* indicate the present state and the previous state of the system, respectively. The output of the PI-like FLC is the incremental change in the control signal *Du(k)*. The control signal is obtained by

$$u(k)=u(k-1)+\Delta u(k) \qquad (5)$$

All MFs for the controller inputs i.e. *e*, *De* and *Du* are defined (Figure 3) on the common normalized domain [-1 1].

The rule base for computing output *Du* is shown in Table I; this is a often used rule-base designed with a 2-dimensional phase plane where the FLC drives the system into the so-called sliding mode [3]. The control rules in Table I are based on the characteristics of the step response. For example, if the output is falling far away from the set point, a large control signal that pulls the output toward the set point is expected, whereas a small control signal is required when the output is near and approaching the set point.

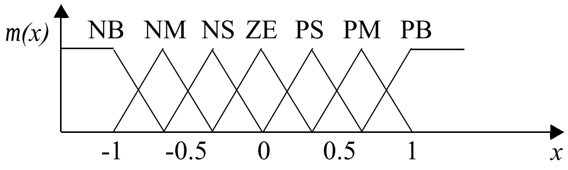

Figure 3: Membership functions of *e, De* and *Du*

Table I: Fuzzy rules for computation of *Du*

e(k)/ e(k)	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

Legend: **NB**: Negative Big; **NM**: Negative Medium; **NS**: Negative Small; **ZE**: Zero; **PS**: Positive Small; **PM**: Positive Medium; **PB**: Positive Big.

Here, triangular MFs are chosen for **NM, NS, ZE, PS, PM** fuzzy sets and trapezoidal MFs are chosen for fuzzy sets **NB** and **PB**.

B. Incremental Fuzzy Gain Scheduling PI Controller

Another category of fuzzy PID controller is composed of a conventional PID control system in conjunction with a set of fuzzy rules and a fuzzy reasoning mechanism to tune the PID gains online. By virtue of fuzzy reasoning, these types of fuzzy PID controllers can adapt themselves to varying environments. Incremental Fuzzy Gain Scheduling PI Controller (IFGSPIC) is a such type controller.

IFGSPIC is similar to the conventional GS controller in changing the gains for varied operating conditions or process dynamics. IFGSPIC provides a fuzzy logic supervised PI control scheme in which parameters of a PI controller are updated online as a function of the operational conditions of the controlled plant, improving the behavior of classical fixed gain conventional PI controller. It combines the advantages of a FLC and a conventional PI controller. The closed-loop system of IFGSPIC is shown as Figure 4.

The IFGSPIC controller has the following form:

$$K_p=K_{p0}+k_p CV_p(e,\Delta e) \qquad (6)$$

$$K_i=K_{i0}+k_i CV_i(e,\Delta e) \qquad (7)$$

$$\begin{aligned} u(t) &= K_p e(t)+K_i\int_0^t e(t)dt=[K_{p0}e(t)+K_{i0}\int_0^t e(t)dt] \\ &\quad +k_p CV_p(e,\Delta e)e(t)+k_i CV_i(e,\Delta e)\int_0^t e(t)dt \\ &= u_c(t)+\Delta u(t) \end{aligned} \qquad (8)$$

where K_{po} and K_{io} represent initial proportional and integral gains obtained by a Ziegler-Nichols tuning method [4], and proportional and integral fuzzy-control matrices are expressed by CV_p and CV_i whose elements are fuzzy gains as functions of error and change of error. The fuzzy coefficients k_p and k_i are scaling factors.

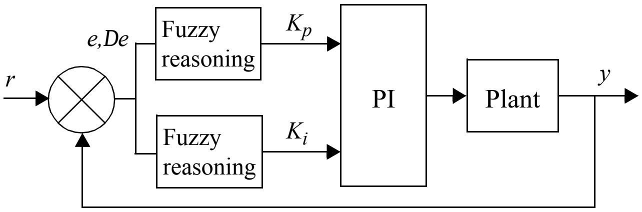

Figure 4: Closed-loop system of IFGSPIC

In eq. (8), there are two terms: the first term is of the conventional PI control, $u_c(t)$, and the second is of incremental output type from fuzzy reasoning, *Du(t)*. Combining the fuzzy reasoning with the conventional PI controller within the framework, the IFGSPIC can properly schedule proportional and integral gains to improve conventional PI controller's performance.

The rule base design of IFGSPIC is based on the desired transient and steady state step responses. The expected incremental output values, which are the fuzzy-matrix elements, are deduced according to the tendencies of error and error sum as shown in Tables II and III. In designing the integral fuzzy matrix CV_i, for example, the error sum term Integral($e(t)dt$) is almost always positive for a step up change. Therefore, the element of integral fuzzy matrix CV_i should be negative to suppress an overshoot and positive to overcome an undershoot [5].

The following 3 steps are used for tuning the IFGSPIC:

Step 1. Use Ziegler-Nichols method to obtain initial values of PI gains, K_{po} and K_{io}.

Step 2. Determine initial value of IFGSPIC's proportional gain according to transient state and disturbance rejection situations. In transient state, big proportional gain to speed up regulation is needed, but this will be at the risk to produce large overshoot. And in steady state, because system error is almost zero, proportional control action is near zero. Considering above two situations, the initial value of proportional gain can be chosen smaller than that obtained from Ziegler-Nichols method and let incremental output of fuzzy reasoning readjust proportional gain around initial value. In this way, the system will have less overshoot and settling time when keeping the same rising time as fixed gain conventional PI controller. From the point view of disturbance rejection, it is expected proportional gain be big enough. Therefore, the initial proportional gain is chose to be 1/2 to 1/3 value obtained from Ziegler-Nichols method. Let this value plus the value of incremental output of fuzzy reasoning to equal to the value obtained from Ziegler-Nichols method, which has good ability at load disturbance rejection [6]. Thus, the system's stability and the ability for anti-disturbance can be guaranteed.

Table II: Fuzzy Rules for Computation of CV_P

e(k)/De(k)	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	PB	PB	PB	ZE	NM	NS	ZE
NM	PB	PB	PB	ZE	NS	ZE	PS
NS	PB	PB	PM	ZE	ZE	PS	PM
ZE	PB	PM	PS	ZE	PS	PM	PB
PS	PM	PS	ZE	ZE	PM	PB	PB
PM	PS	ZE	NS	ZE	PB	PB	PB
PB	ZE	NS	NM	ZE	PB	PB	PB

Table III: Fuzzy Rules for Computation of CV_i

e(k)/De(k)	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Step 3. Determine initial value of IFGSPIC integral gains according to steady state. Because integral control action is primarily to reduce the steady state error, the initial value of integral gain obtained from Ziegler-Nichols method is kept unchanged. When the system enters steady state, the incremental output of fuzzy reasoning is near zero, so this initial value will keep the system at high accuracy and fewer tendencies to initiate system oscillations.

IV. IMPLEMENTING FLC USING EMTP RV

To implement FLC using EMTP RV, several building blocks in the control library of EMTP RV are used. Figure 5 gives an example of the detailed scheme of the FLC with four rules. As usual, FLC has four parts: fuzzification, fuzzy rule base, fuzzy inference engine, and defuzzification.

The detailed implementation of the FLC, based on the example shown in Figure 5, is as follows:

A. Fuzzification

For fuzzification, there are two parts involved: error (*e*) fuzzification and the change of error (*De*) fuzzification. The table function item of the control library in EMTP RV is used for fuzzification. Since the MFs of error and the change of error are represented by two fuzzy subsets from negative (N) to positive (P), four table function items (Tab1 to Tab4) are used to get these fuzzy sets, as shown in Figure 5. The table function item has an interpolation function between two given points. Linear interpolation makes it easy to obtain triangular and trapezoidal MFs.

B. Fuzzy rule base

From Figure 5, it is noted that there are 4 rules, from *r1* to *r4*, which form the rule base (i.e. if *x* and *y*, then *z*).

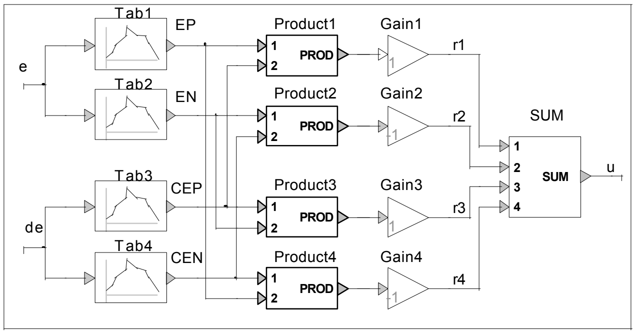

Figure 5: Scheme of FLC using EMTP RV

C. Fuzzy inference engine and defuzzification

The fuzzy inference engine and defuzzification can be formulated from a combination of product, gain, and SUM items which come from the EMTP RV control library, based on eq. (4). In Figure 5, the gain blocks (Gain1 to Gain4) represent the centers ($z_i^{'}$) of the fuzzy inference engine. Two-input product blocks (Product1 to Product4) are used for an algebraic product fuzzy conjunction i.e. $m_{Ai}(x)m_{Bi}(y)$. The product blocks together with gain blocks implement a product fuzzy implication (Larsen implication) i.e. $z_i^{'} m_{Ai}(x)m_{Bi}(y)$. A sum block (SUM) is used to accomplish the maximum s-norm rule aggregation i.e. SUM $(z_i^{'} m_{Ai}(x)m_{Bi}(y))$.

Using the design principles mentioned above, it is easy to design a rule base which includes more than 4 rules. In the following simulation, a rule base with 49 rules is used.

V. SIMULATION RESULTS & DISCUSSION

To examine the transient as well as the steady state behaviors of controllers (conventional PI controller, PI-like FLC, and IFGSPIC), a fourth-order test plant with the following transfer function is used:

$$G(s) = \frac{27}{(s+1)(s+3)^3} \tag{9}$$

In order to compare the performance of the controllers, the following performance measures will be used: rising time (t_r), percent maximum overshoot (%OS), 5% settling time (t_s), integral of the squared error (ISE) and integral of the absolute error (IAE) [7]. The comparative performance of the controllers is tabulated in Tables IV, V and VI.

In all cases of the fuzzy rule-based systems, Larsen inference and center average defuzzification are used. The Mamdani inference was also tried but no noticeable differences in control performance with these two inference methods was observed. The Larsen inference method is preferred, as it is a very simple and fast algorithm, which is an important consideration for real-time implementation. During the simulation, trapezoidal method is used for the numerical integration in EMTP RV.

The conventional PI controller parameters are determined by Ziegler-Nichols method, i.e. K_p=0.45×K_r=2.304, Ti=0.85×Tr=2.321, and K_i=K_p/T_i=0.992. The parameters K_r=5.12 and T_r=2.73 are obtained experimentally.

The initial value of proportional and integral gains of IFGSPIC are selected to be K_p=1 and K_i=0.992. Compared to the PI controller, the K_p of the IFGSPIC is reduced to 1 from 2.304. Considering the adaptive function of IFGSPIC, this gain reduction will lead to lower overshoot and settling time whilst maintaining almost the same rise time, as shown in section III. The initial value of integral gain obtained from Ziegler-Nichols method is kept unchanged. When system enters steady state, the output of IFGSPIC is zero, so the initial value of integral gain will keep the system at high accuracy and have lower tendency for oscillations. Thus, IFGSPIC is also a hybrid controller: at transient state, it is a FLC to get faster response and in the steady state, it is a conventional PI controller to obtain higher accuracy.

The conventional PI controller, PI-like FLC and IFGSPIC (Figures. 6-8) are implemented using EMTP RV.

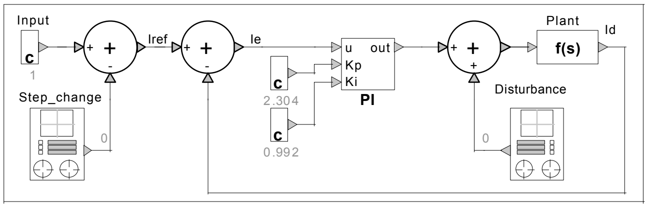

Figure 6: Conventional PI controller

A. Step Responses

From Table IV and Figure 9, it can be seen that IFGSPIC has the best performance, i.e. a faster response and a smaller overshoot. From the point view of ISE and IAE performance criteria, the PI-like FLC is even worse than a conventional PI controller. Several reasons explain these results:

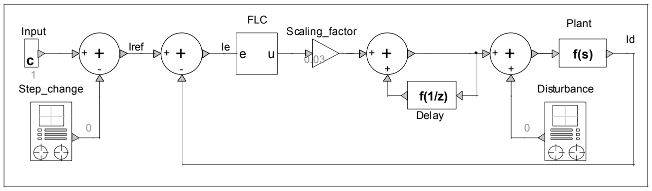

Figure 7: PI-like fuzzy logic controller

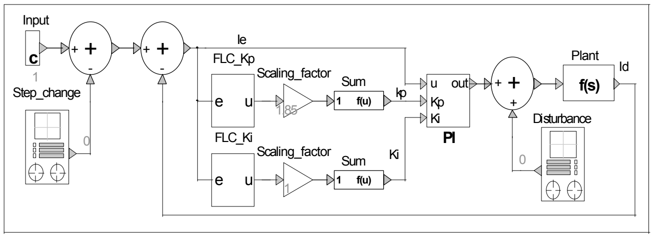

Figure 8: Incremental fuzzy gain-scheduling PI controller

- PI-like FLC obtains the control signal incrementally starting from zero, while the IFGSPIC obtains the control signal directly from the initial PI controller that has a larger output during startup,
- PI-like FLC is usually quite satisfactory for operating with lower-order systems. For higher-order systems and particularly nonlinear systems, the performance is usually poorer [8], and
- PI-Like FLC hasn't obviously separated proportional and integral control actions and this is so-called control-action composition, i.e. they cannot decompose the output for proportional and integral control action [9].

Following the above-mentioned observations, for all further investigations, only the IFGSPIC will be considered and compared with the conventional PI controller.

Table IV: Comparison of performance of the controllers

Type	t_r(s)	%OS	t_s(s)	ISE	IAE
PI	1.54	35.9	8.35	1.063	2.129
PI-like	2.84	7.7	7.68	1.58	2.358
IFGSPIC	1.92	2.1	1.72	0.8159	1.073

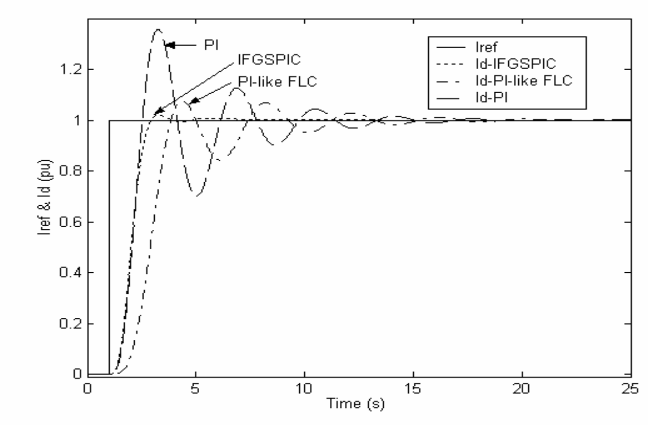

Figure 9: Comparison of step responses of the controllers

B. Step Responses with Disturbance

A comparison of results in Figure 10 and Table V shows that the performance of the IFGSPIC is consistently better than the conventional PI controller under the disturbance N= -10 pu (Figure 8) at 10 s.

Table V: Performance analysis with disturbance

Type	t_r(s)	%OS	t_s(s)	ISE	IAE
PI	1.54	35.9	8.35	1.354	3.371
IFGSPIC	1.92	2.1	1.72	0.93	1.761

C. Responses with a 20% Step-down Change

A comparison of results from Figure 11 and Table VI shows again that the IFGSPIC outperforms the conventional PI controller with a 20% step change in Iref at 10 s.

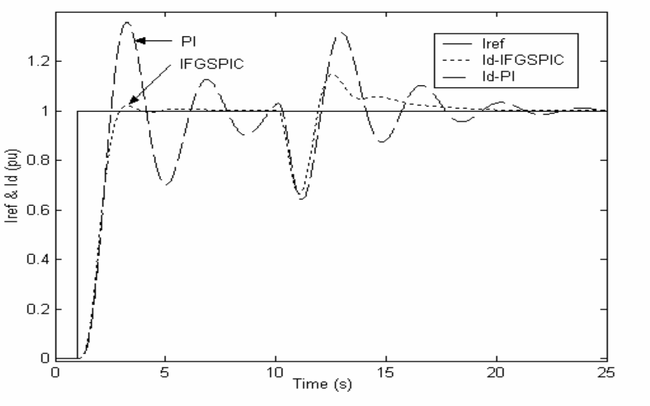

Figure 10: Comparison of the PI & IFGSPIC controllers under disturbance

D. On-line Adaptation of IFGSPIC

The most important property of IFGSPIC is its ability of on-line adaptation. Figure 12 shows the on-line adaptation of the controller's proportional gain K_p and integral gain K_i when the system begins startup and has a 20% step change in Iref at 10s. When system begins startup, the controller updates K_p and K_i on-line using fuzzy inference in order to achieve a good behavior according to desired system's performance. For example, when step up response increases from zero to reference value, *Du(t)* should be changed from $PB \to ZE \to NB$ to prevent a large overshoot and also provide a fast response. The on-line adaptation makes the proportional gain K_p updated through changing the incremental output value according to fuzzy-matrix CV_i from $PB \to ZE$ and integral gain K_i updated through changing the incremental output value according to fuzzy-matrix from $PB \to ZE \to NB$, thus *Du(t)* can follow the desired change mentioned above. It is the on-line adaptation of the parameters of IFGSPIC that guarantees the system achieves desired performance at transient state, thus improving the behavior of the classical fixed gain conventional PI controllers, which are usually employed.

When system approaches steady state, the system's output variable converges to a reference value. As a result, error (e) becomes near zero. From Figure 12, it can be seen that integral gain K_i tends towards its initial value, (which was obtained from Ziegler-Nichols method) while proportional gain K_p does not affect steady state performance according to the following equation when the error (e) is zero.

$$u(k) = K_p e(k) + TK_i \sum_{n=0}^{k} e(n) \tag{10}$$

Table VI: Performance analysis with step change

Type	t_r(s)	%OS	t_s(s)	ISE	IAE
PI	1.54	35.9	8.35	1.159	2.89
IFGSPIC	1.92	2.1	1.72	0.8879	1.559

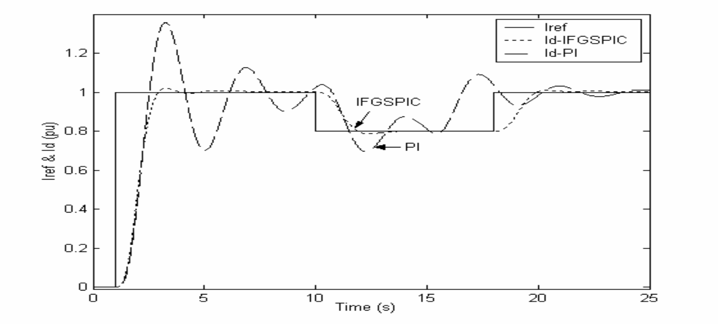

Figure 11: Comparison of PI-IFGSPIC controllers with step change in Iref

Hence, the on-line adaptation ability of IFGSPIC makes the controller look like a hybrid controller. The fuzzy inference leads to a fast response when system is in the transient state. A conventional PI controller with a set of fixed gains can be achieved after the transient stage of the process response, which can guarantee the accuracy, stability and disturbance rejection [6].

Therefore, IFGSPIC combines a fuzzy logic controller and conventional PI controller with parameters tuned by Ziegler-Nichols method. A quick response, high accuracy and stability can be achieved by this combination.

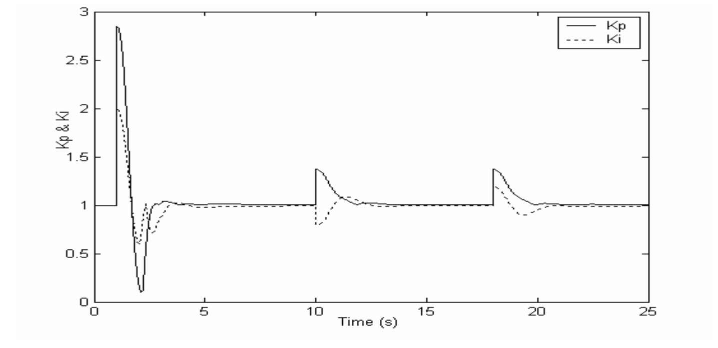

Figure 12: Proportional and Integral gain adaptation

E. Chopper Current Control System

To verify the IFGSPIC, the controller has been applied to a chopper current control system under the EMTP RV simulation environment with a reference step change from 0.8 pu to 0.75 pu at 4.2 s and from 0.75 pu to 0.8 pu at 5 s. The results (shown in Figures 13 and 14) indicate the advantages of the IFGSPIC again.

VI. CONCLUSION

Simulation results show that the fourth-order plant and chopper current control system can be satisfactorily controlled by the IFGSPIC. It yields better control performance than the conventional PI controller does, which is confirmed by comparing performance indexes such as rising time, the percent maximum overshoot, the settling time, ISE and IAE. Future work will concentrate on the use of the controller with a HVDC rectifier.

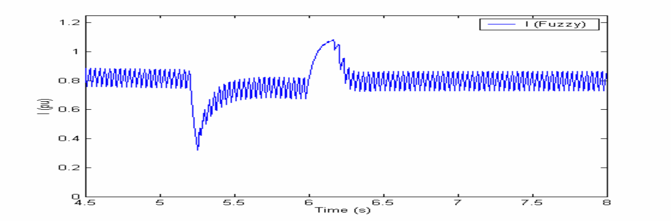

Figure 13: IFGSPIC controller with a step change in Iref

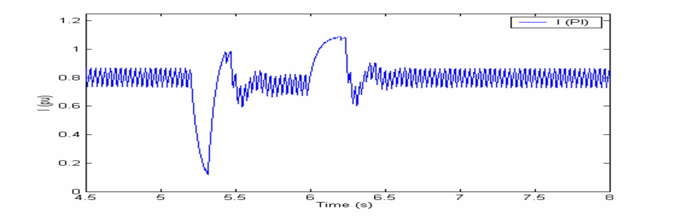

Figure 14: PI controller with a step change in Iref

VII. ACKNOWLEDGMENT

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