

# Transient response improvement of direct current using supplementary control based on ANFIS for rectifier in HVDC

I Made Ginarsa, Agung Budi Muljono, I Made Ari Nrartha, Sultan

Department of Electrical Engineering, University of Mataram, Indonesia

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## ABSTRACT

Current control scheme is commonly used in high voltage direct current (HVDC) to transmit power delivery. This scheme is done by adjusting trigger angle to regulate direct current (DC) in thyristor devices. The adaptive neuro-fuzzy inference system (ANFIS) control is widely applied for start and fault operation. But, solution for transient response of DC current in HVDC system is not clearly studied before. In this paper, supplementary control (SC) based on ANFIS is proposed to improve the transient response of the current. The SC control is designed by learning-processes and SC parameters are obtained by data-training automatically. For current reference at 1.05 pu and up-ramp at 20 pu/s, maximum overshoot is achieved at 5.12% and 7.72% for the SC and proportional integral controller (PIC), respectively. When the up-ramp is increased to 28 pu/s, the maximum overshoot is achieved at 10.01% for the SC. While, the peak overshoot for the PIC is 14.28%.

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## Corresponding Author:

I Made Ginarsa,

Department of Electrical Engineering,

University of Mataram,

Jln. Majapahit No. 62, Mataram 63125 NTB, Indonesia.

Email: kadekgin@unram.ac.id

## 1. INTRODUCTION

Indonesia is an archipelago country that consists of main-islands such as: Sumatera, Java, Sulawesi, Kalimantan, Nusa Tenggara, Maluku and Papua. Most of the main-island electrical power systems are independent and separate from each other. Application of high voltage alternating current (HVAC) through long distance submarine power cable (SPC) is difficult to be built because the SPC has very high line-charging, high reactive power losses and stability problems [1]. While, high voltage direct current (HVDC) system is very promising to overcome these problems and to be implemented in Indonesia especially for long distance HVDC using SPC. Pre-analysis of Java-Sumatra HVDC transmission has been conducted to realize the HVDC application in Indonesia power system inter-connection [2, 3].

The HVDC transmission is applied to transmit bulk electric power through transmission line over a long distance using overhead conductors or SPC [4]. The HVDC technology has several advantages compared to competing HVAC technology such as: Power plant can be located far from consumer, not need reactive power compensation in long distance HVDC transmission, can be inter-connected to HVAC for difference frequencies, to transmit more capacity of power delivery [5, 6]. Also, development and operation costs of the HVDC are cheaper than the HVAC for long-distance transmission and friendly for environment [7]. A HVDC-link connected to a HVAC will prevent fault and oscillation propagate to neighbor the HVAC. Moreover, the HVDC is able to improve stability of inter-connected HVAC by modulating power in response to small/large disturbances [8], line commutated converter (LCC)-HVDC links are applied to enhance stability of permanent magnet synchronous generator offshore wind turbine [9] and

large-scale integration of wind, solar and marine-current generation [10] fed to multi-machine power systems (PS).

To help the HVDC in operation and control managements, a comprehensive small-signal model of a LCC-voltage source converter (VSC) HVDC-link and their eigen-analysis of the model are built and impact of parameter to system damping is studied. The DC-current control parameters of LCC, DC-voltage control parameters of VSC DC-side capacitor of VSC and smoothing reactor of LCC have large effect to the damping oscillatory mode of power systems. Also, larger PI gain of the VSC, and smaller PI gain of the LCC are able to improve damping of the dominant mode [11]. A model for hybrid multi-in-feed HVDC (H-MIDC) link and its controller are developed to simulate small-signal model. The H-MIDC link is located close in a common receiving AC grid. The dynamic performances of H-MIDC are improved using optimized parameters control [12]. Analysis of HVDC-line with off-shore resources and storage devices is done using optimal power flow strategy [13]. Some differential equation sets are designed to develop HVDC in average-value model to simplify the HVDC model without including switching-device mechanism and neglected high frequency [14], and this model is applied to power system analysis [15]. Dynamic properties in both AC/DC of HVDC-link are presented on frequency-domain model. This model is used to control and stability analysis of overall power systems, that Part I describes fixed-commutation overlap method [16] and Part II explains the model upgraded by varying-overlap angle [17].

However, HVDC control has non-linear characteristics include several properties in converter/inverter devices, transformer saturation and presence of filters in AC/DC-side and harmonic generation. The non-linear characteristics make the regulation of HVDC are complicated and challenged in PS and power electronic fields. Predictive control is proposed to improve PS stability [18]. Control parameter is optimized to improve the HVDC performance using electromagnetic transient analysis program [19]. The HVDC control is simplified by building a novel space-vector pulse width modulation (SVPWM) [20] and simplification of SVPWM 3-dimension control is applied to regulate 3-phase 4-leg of inverters [21].

Artificial intelligent application is very attractive research and it is implemented in some fields such as: Genetic algorithm to optimize robustness and efficiency of micro-grid DC solar-system structures [22], firefly algorithm to optimize PID parameter of automatic generation control in multi-area [23]. Grey wolf optimizer (GWO) is used to optimize power flow wind farm integrated to PS [24], to optimize power allocation to realize plug-and-play capability of micro-grid system [25], to minimize operating cost and active power loss by optimizing reactive power generation [26] and to estimate input-output parameters of thermal plant [27]. The GWO is also applied on power system stabilizer to damp local oscillation in multi-machine [28] and inter-area oscillation in wide-area [29]. While, development of neural control is done in [30] to improve stability of power transmission and in [31] to help dispatcher in decision making on mapping of PS fault instantaneously. Fuzzy control is developed to design of wind-PV combined-generator model [32], to regulate induction motor speed combined by proportional-integral control [33], and fuzzy type-2 to control permanent magnet synchronous machine through digital-signal processing [34]. The neural network-fuzzy model is applied to advance direct power control for grid-connected to distributed generator [35]. An adaptive neuro-fuzzy inference system (ANFIS) has been designed to regulate converter [36] and inverter [37] of HVDC-line, and to control voltage collapse in PS [38]. Also, the ANFIS scheme is used to control, detect fault, and protect [39, 40] of HVDC, and to protect HVDC-light from AC fault [41]. Moreover, combination of ANFIS and fuzzy type-2 has been used to maintain large-scale PS stability [42].

Transient responses of voltage/current are very important in PS and power electronic researches because these responses should be constrained to protect the systems and devices from over-voltage/current on its operation. To improve transient response, some control schemes are proposed such as: ANFIS algorithm based on additional PID-loop to improve transient voltage response in PS [43], feed-forward compensation method [44], feed-forward capacitor [45], triangular wave generator through to adjust its slope [46] for DC-DC converters and feed-forward compensation model for DC-AC converter based on space vector-pulse width modulation [47]. However, research topic of transient responses improvement in HVDC using ANFIS control scheme has not been clearly discussed. This remaining paper is organized as follows: Design of supplementary control based on ANFIS model is described in Section 2. Results and discussion are explained in Section 3. And, finally conclusion is summarized in Section 4.

## 2. DESIGN OF SUPPLEMENTARY CONTROL BASED ON ANFIS MODEL

Supplementary control (SC) is proposed in thyristor-based rectifier of HVDC system to help the PI regulator to reduce transient direct current response, especially when the up-ramp value was higher (such as: 20 pu/s or more). Where, the SC is defined by PI control plus ANFIS-based control. The HVDC and its control blocks are taken from [48] and controller of the system is shown in Figure 1(a). While, current

reference pattern of HVDC at start-up is illustrated in Figure 1(b). The ANFIS-based controller is built by ANFIS model [49]. Block diagram of SC is depicted in Figure 2.

The ANFIS controller of SC is developed by training process. Inputs data of training process are current error ( $I_{err}$ ), its derivative ( $dI_{err}$ ) and additional trigger angle from the supplementary control ( $Alpha_{SC}$ ,  $\alpha_{SC}$ ). Where, the current error was obtained by difference of direct current ( $I_d$ ) and reference current ( $I_{ref}$ ). In the training process, the ( $I_{err}$ ;  $dI_{err}$ ) and ( $Alpha_{SC}$ ,  $\alpha_{SC}$ ) were formed into 5,000 input-output matrix data. The training process was done in off-line session. Result of the training process was a SC controller based on ANFIS model as shown in Figure 3. The ANFIS structure and pattern of input-output control are shown in Figures 4(a) and (b), respectively. Furthermore, the ANFIS model is embedded to fuzzy controller in Simulink [50] model as described in Figure 3. Next, the SC performance is evaluated in Section 3.

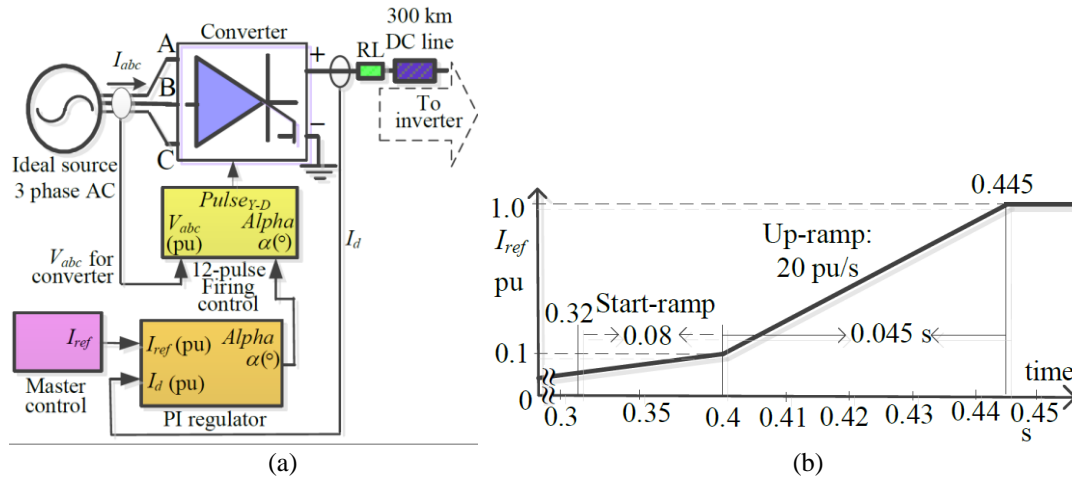


Figure 1. Control scheme for HVDC transmission system, (a) diagram block of thyristor-based rectifier, (b) current reference ( $I_{ref}$ ) pattern at up-ramp 20 pu/s

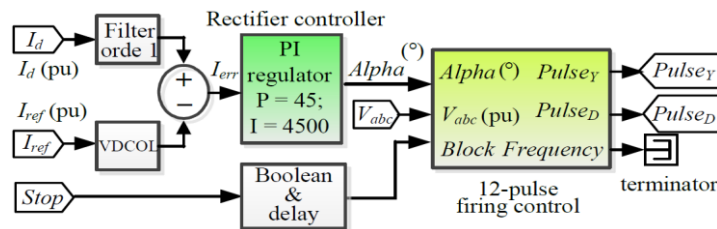


Figure 2. Trigger angle ( $Alpha$ ) controller using PI regulator

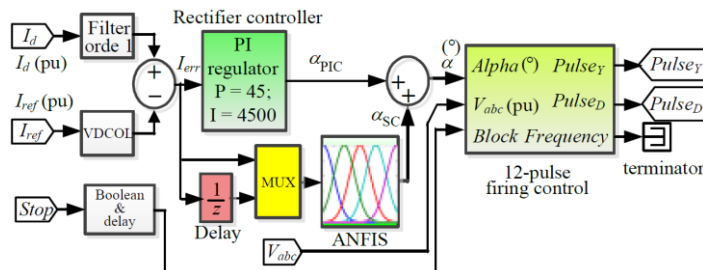


Figure 3. Supplementary controller (SC) to improve transient current response

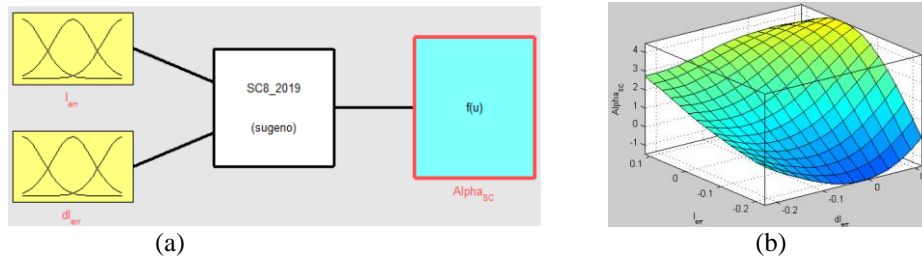


Figure 4. Supplementary control (SC) based on ANFIS Sugeno model, (a) ANFIS structure for SC, (b) pattern of input-output control

### 3. RESULTS AND DISCUSSION

In this research, simulation was done by using Matlab/Simulink [50] on a PC computer. Which is specified as follows: Proc. Intel-i5-7400, cache capacity 6,0 MB, Freq. 3.0 GHz, LGA 1151 windows 7 operating system. The SC was tested to regulate firing angle on rectifier-side of HVDC system.

#### 3.1. Improvement of transient response when final value of current reference set at 0.95 pu

In this case, PI controller parameters were set at the default values  $P=4500$ ; and  $I = 45$  [48]. The master controller parameters were set as follows. Up-ramp rate was increased at the values of 20, 22, 24, 26 and 28 pu/s. Moreover, the up-ramp time and up-ramp final value were taken at the time of 0.3 s and the value of 0.95 pu, respectively. The simulation results are described in Figures 5, 6 and listed in Table 1.

Figure 5 and Table 1 show the transient responses of direct current for respective controllers when the up-ramp rate of current reference was set at 20 pu/s. There are depicted that response parameters for PI controller (PIC) were as follows: 9.85%, 3.843%, 0.459 s, 0.548 s and  $5.953 \times 10^{-2}\%$  for maximum overshoot ( $M_p$ ), start-time error (estr), peak time (tp), settling time ( $t_s$ ) and steady-state error (ess), respectively. Meanwhile, the response parameters that given by SC were as follows: 5.63%, 3.797%, 0.458 s, 0.545 s and  $3.233 \times 10^{-2}\%$  for maximum overshoot, start-time error, peak time, settling time and steady-state error, respectively. Figure 6 and Table 1 illustrate the transient responses when the up-ramp rate of current reference was increased to 28 pu/s. Responses of the PI controller were as follows: 15.18%, 2.708%, 0.452 s, 0.568 s and  $5.651 \times 10^{-2}\%$  for maximum overshoot, start-time error, peak time, settling time and steady-state error. While, the responses that given by the SC were: 9.77%, 2.856 %, 0.451 s, 0.550 s and  $2.564 \times 10^{-2}\%$  for maximum overshoot, start-time error, peak time, settling time and steady-state error, respectively. The SC is able to improve the transient response of direct current based on the response parameters are given in this scenario.

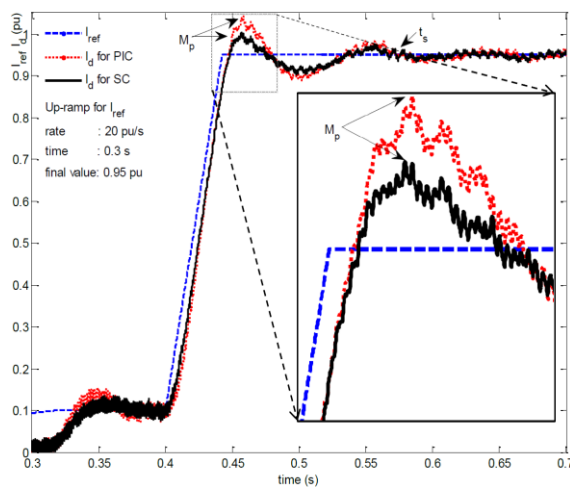


Figure 5. Transient response improvement for direct current at current reference 0.95 pu.

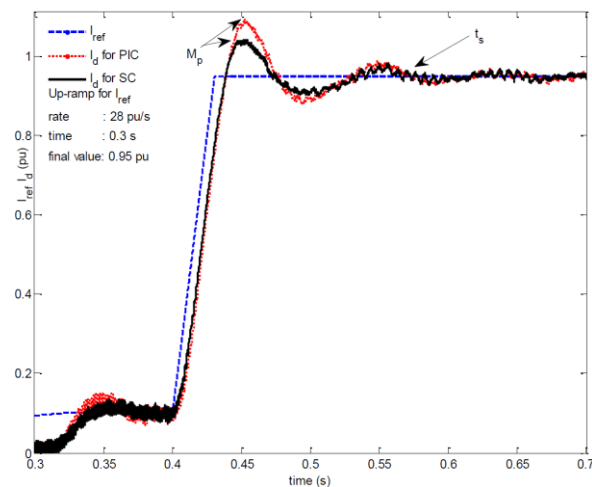


Figure 6. Transient response for current reference 0.95 and up-ramp 28.0 pu/s.

Table 1. The performance of SC when final value of current reference at 0.95 pu.

up-ramp (pu/s)	PI control (PIC)					Supplementary control (SC)				
	$M_p$ (%)	$e_{str}$ (%)	$t_p$ (t)	$t_s$ (t)	$e_{ss}$ $\times 10^{-2}$ (%)	$M_p$ (%)	$e_{str}$ (%)	$t_p$ (t)	$t_s$ (t)	$e_{ss}$ $\times 10^{-2}$ (%)
20	9.85	3.843	0.459	0.548	5.953	5.63	3.797	0.458	0.545	3.233
22	11.84	3.446	0.461	0.557	0.669	6.91	3.666	0.454	0.546	2.295
24	13.27	3.156	0.460	0.561	2.054	7.92	3.415	0.453	0.547	4.574
26	14.29	3.157	0.454	0.565	4.209	9.86	3.201	0.453	0.548	4.011
28	15.18	2.708	0.452	0.568	5.651	9.77	2.856	0.451	0.550	2.564

**3.2. Performance of SC when the final value of current reference set at 1.0 pu**

Furthermore, the final value of current reference was increased to 1.0 pu. The up-ramp rates and up-ramp time were set as same as the values and time before. The results are depicted in Figures 7, 8 and in Table 2. From Figure 7 and Table 2 we can see that the maximum overshoot was achieved at the value of 8.96 and 5.73% for the PIC and SC when the up-ramp rate at 20 pu/s, respectively. The start-time error was at the values of 3.638 and 4.025%. Peak time was at time 0.464 s for the both controllers. The settling time was achieved at time 0.568 and 0.550 s. The steady-state error was achieved at the values of  $(3.042$  and  $0.368) \times 10^{-2}\%$  for the PIC and SC, respectively. Figure 7 shows that maximum overshoot of the PI controller is higher than the supplementary controller.

The Figure 8 and Table 2 shows maximum overshoot was achieved at the value of 14.22 and 9.75% for the PI controller and supplementary controller when the up-ramp rate at 28 pu/s, respectively. The start-time error was at the values of 2.451 and 2.627%. Peak time was at time 0.452 and 0.451 s. The settling time was achieved at time 0.579 and 0.569 s. And, the steady-state error was at the values of  $(0.202$  and  $0.374) \times 10^{-2}\%$  for the PI controller and supplementary controller, respectively.

It is found that the maximum overshoot of direct current equipped by supplementary controller is lower than PI controller. Also, settling time of the supplementary controller is shorter than the other. It is found that the supplementary controller is more effective to reduce peak overshoot of direct current than the PI controller in this scenario.

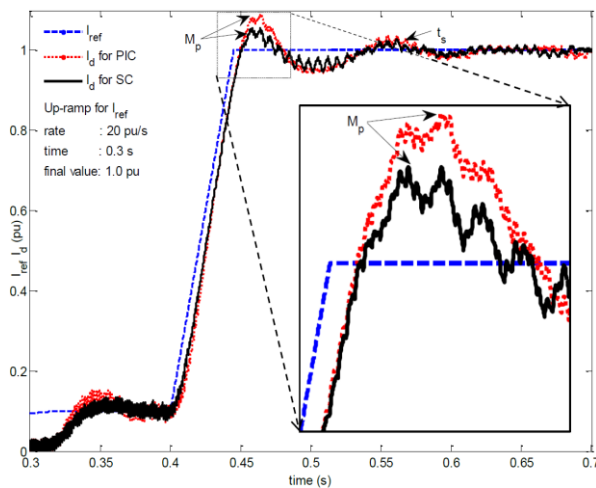


Figure 7. Transient response for current reference 1.0

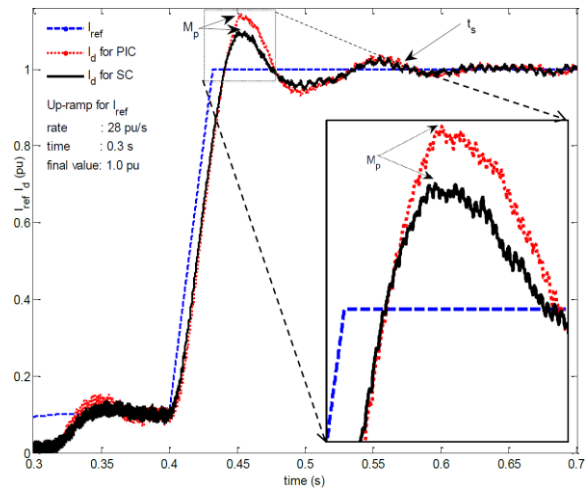


Figure 8. Transient response for current reference 1.0 and up-ramp 28.0 pu/s

Table 2. The performance of supplementary control at current reference = 1.0 pu.

up-ramp (pu/s)	PI control (PIC)					Supplementary control (SC)				
	$M_p$ (%)	$e_{str}$ (%)	$t_p$ (t)	$t_s$ (t)	$e_{ss}$ $\times 10^{-2}$ (%)	$M_p$ (%)	$e_{str}$ (%)	$t_p$ (t)	$t_s$ (t)	$e_{ss}$ $\times 10^{-2}$ (%)
20	8.96	3.638	0.464	0.568	3.042	5.73	4.025	0.464	0.550	0.368
22	10.65	3.326	0.461	0.571	1.264	7.36	3.686	0.459	0.553	1.901
24	12.03	3.036	0.460	0.573	2.154	7.73	3.321	0.453	0.559	0.906
26	13.25	3.036	0.454	0.575	0.380	9.02	2.972	0.453	0.564	0.072
28	14.22	2.451	0.452	0.579	0.202	9.75	2.627	0.451	0.569	0.374

### 3.3. Improvement of direct current transient response at 1.05 pu

Moreover, the system is tested by increasing the final value of direct current again to 1.05 pu. The results are described in Figures 9, 10 and Table 3. Table 3 depicts maximum overshoots of direct current were achieved at the values of 7.72-14.28% for the PIC when the up-ramp rates were taken at 20-28 pu/s, respectively. Errors at start-time are achieved at the values of 3.63-2.46%. The settling time for the PIC were at times of 0.571-0.578 s. The steady-state errors were achieved at the values of  $(3.042-0.202) \times 10^{-2}\%$ . Figure 9 shows transient responses of DC current for PI and SC for up-ramp rates at 20 pu/s.

While, the maximum overshoots of direct current were achieved at the values of 5.73-9.75% for the SC when the up-ramp rates were at 20-28 pu/s. Errors at start-time were at the values of 4.025-2.627%. The settling times were at times of 0.550-0.569 s. The steady-state errors were achieved at the values of  $(0.368-0.374) \times 10^{-2}\%$ . Also, transient response of DC current is depicted in Figure 10 for the PIC and SC controller, respectively, when the up-ramp rate is given at 28 pu/s.

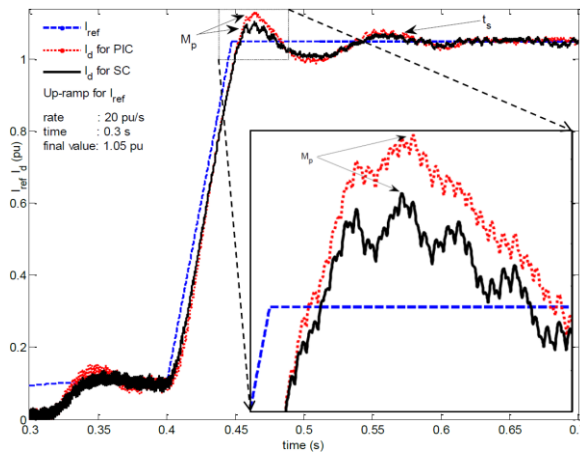


Figure 9. Transient response improvement for current reference 1.05 pu.

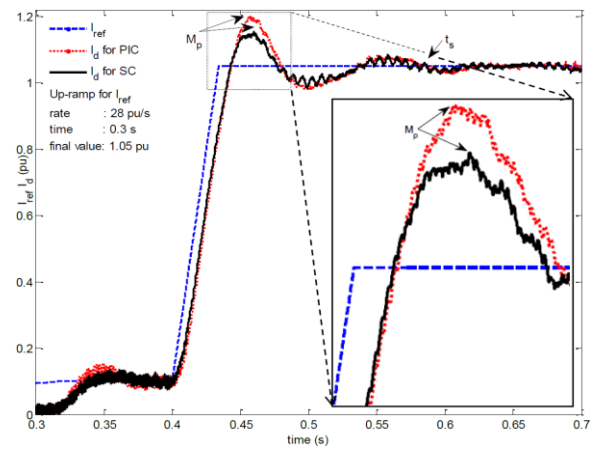


Figure 10. Transient response improvement for current reference 1.05 pu and up-ramp 28.0 pu/s.

Based on the results, peak overshoot and settling time of SC are lower and shorter than the peak overshoot and settling of the PIC. On the other hand, the error at start-time and steady state error for all controllers are small ( $< 5\%$ ) and very small ( $< 10^{-2}\%$ ), respectively. The SC is more effective to reduce the transient response of direct current than the PIC for the up-ramp of reference current at 20-28 pu/s.

Table 3. The performance of supplementary control when reference current was set at 1.05 pu.

up-ramp (pu/s)	PI control (PIC)					Supplementary control (SC)				
	$M_p$ (%)	$e_{str}$ (%)	$t_p$ (t)	$t_s$ (t)	$e_{ss} \times 10^{-2}$ (%)	$M_p$ (%)	$e_{str}$ (%)	$t_p$ (t)	$t_s$ (t)	$e_{ss} \times 10^{-2}$ (%)
20	7.72	3.215	0.466	0.571	2.863	5.12	4.343	0.463	0.548	4.844
22	10.12	3.611	0.463	0.573	4.906	5.99	4.302	0.460	0.552	3.787
24	12.34	3.293	0.461	0.575	6.537	6.64	3.518	0.460	0.563	0.967
26	13.38	3.293	0.460	0.579	6.319	8.22	3.220	0.455	0.568	1.936
28	14.28	2.793	0.457	0.580	7.028	10.01	2.992	0.460	0.570	2.735

## 4. CONCLUSION

Application of SC for HVDC based on ANFIS model is done in this research. The design process of ANFIS model is also explained before the control applied to the HVDC system. Simulation results of HVDC with SC are compared to the results from proportional integral control (PIC) to verify the validity of the proposed controller. The results show that maximum overshoots are achieved at 5.63% and 9.85% for SC and PIC, when current reference and up-ramp are set at 0.95 pu and 20 pu/s. Moreover, the current reference and up-ramp are increased to 1.05 pu and 28 pu/s. The maximum overshoots for SC and PIC are achieved at 10.01% and 14.01% and 14.28%, respectively. The proposed control is able to improve the transient response by reducing the maximum overshoot for all simulations.

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## BIOGRAPHIES OF AUTHORS



I Made Ginarsa was born in Darmasaba, Badung Bali Indonesia 1970. He received in B.Eng, M.Eng and Ph.D in elect. eng. UNUD (1997), UGM (2001) and ITS (2012). Since 1999 he was a lecturer at Elect. Eng., University of Mataram. In 2010 he was a member of EPS Lab., Kumamoto Univ. His research interests are dynamic and stability, nonlinear dynamic, voltage stability and artificial intelligent application in power systems. He was an active author, co-author and invited reviewer on national and international publications.





Agung B. Muljono, was born in Purwodadi Grobogan Indonesia, 1971. In 1998 he joined University of Mataram, Indonesia, as a lecturer. His research interests include transmission and distribution, dynamic and stability, artificial intelligent application, and energy planning and distributed generation in power systems. He received the B. Eng and M. Eng. in Electrical Eng. from Malang Institute of Technology (1996) and UGM (2000), respectively. He was an active author and co-author research papers and served as editorial board in Dielektrika Journal.



I Made Ari Nrartha, was born in Denpasar Bali Indonesia, 1973. He received in B.Eng and M.Eng in electrical eng. from ITS (1997) and UGM (2001). Since 1999 he was a lecturer at Electrical Eng., University of Mataram. His research interests are power system dynamic and stability, transmission and distribution, optimization, power quality and artificial intelligent application in power systems. He was an active author and co-author research papers in national and international journal, and served as editorial board in Dielektrika Journal.



S. Sultan, was born in Bulukumba South Sulawesi, Indonesia. He received the B. Eng. and M.Eng. degrees in Electrical Eng. from Hassanudin University (1995) and UGM (2005), respectively. In 1997 he was a lecturer in University of Mataram, Indonesia. His research interests include power system transmission and distribution, power system dynamic and stability in power systems. He was an active author and co-author research papers in national and international journal, and served as editor in chief of Dielektrika Journal 2010-2018.