Application of AI for Frequency Normalization of Solar PV-Thermal Electrical Power System

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***Abstract* — Grid-connected solar-PV schemes have become a significant part of the energy balance in the power system to satisfy the growing request for clean, affordable energy. This study attempts to link solar-PV generation with conventional thermal power plants and to integrate the control zone resulting in a hybrid solar PV-thermal electric power system using an AC tie line. An analysis of the frequency dynamics for varying load conditions of the interconnected system is studied. Diverse approaches of proportional, integral, and proportional-integral fuzzy logic built controllers are design and tested in order to match the electric power with variable loads of the system and hence to normalize the frequency of the system in shortest possible time. A comparative analysis of the design topologies is conducted out for the PV-Thermal scheme. Results obtain from the implementation are shown to justify the performance of proposed control efforts, using MATLAB software tool.**

Keywords— Solar PV-Thermal electrical power system, frequency dynamics, Proportional, Integral, FLPI control.

I. INTRODUCTION

Present-day standards with respect to electricity supply is to deliver consistent and continuous energy to the customer with consistent and unchanged power quality in a safe and secure manner. Frequency robustness is a critical aspect necessary for achieving minimum standards of electricity supply for progressive and developing nations. By creating, an equilibrium between energy supplied and energy required, we maintain frequency robustness. We install frequency regulators on generators since the load duration curve varies over the day. Thus, the power delivered is within the marginal frequency deviation of ±1 percent from the South African standard frequency of 50 Hz.

A two-step control process helps to achieve frequency robustness. Owing to the imbalance between power supplied and power required, the primary control movement first initiates corrective measures to normalize the imbalance through the droop control technique. Due to the response of the primary control being insufficient and results in delayed correction and frequency deviation for prolonged periods. This is undesirable. Hence, the secondary control responds in a swift action to reestablish the permitted operational frequency. The power control areas are interconnected using the AC tie line, which in turn facilitates the transfer of power between power control areas. In addition, the power capacity of the specific power control area must be able to meet the power requirement as dictated by the load while coping with the power-sharing facilitated through AC tie lines keeping frequency and power interchanges at the scheduled values; and achieved by measuring a control error signal known as the area control error (ACE).

Solar PV generation is high on the South African power plan as an alternative energy source to supplement the growing energy deficiency. Solar PV is sustainable and environmental friendly. The integration of PV power into electricity grids introduces system frequency problems due to the inherent intermittent nature of PV power generation systems. Despite the challenges presented by solar power generation and power system integration, solar power generation as an alternate power source is preferred due to the availability of solar radiation.

Classical controllers are unable to mitigate transient frequency deviation. The design and implementation of LFC controllers to improve frequency robustness in power systems have progressed over the years. Researchers have employed various design strategies to keep the system frequency and tie-line power within controlled limits. The literature on frequency stability approaches for thermal power plants based on coal generation is available. However, there are limited attempts that explore PV power system generation or integrated PV thermal systems [1-4]. The solar PV based generation can be considered as one control region with independent electric power. This control region can interconnect with thermal generation control regions through the AC tie-line. It ensures that the requirements for electricity are fulfilled, and the frequency reliability for dynamic demand of load in the network is preserved..

Some researchers have used artificial intelligence (AI) tools, such as fuzzy logic (FL) [4-9], to improve the limitations offered by conventional frequency controllers in order to address the frequency normalization problem. Robustness and reliability make the fuzzy controllers useful in solving a wide range of control problems [10]. Several practical problems have fuzzy logic applied. This includes the control of warm water [11], robot [12], heat exchangers [13], power system, and nuclear reactors [14]. A fuzzy logic system typically includes a fuzzifier, rule base, inference engines, and defuzzifier to produce the required output [15].

The modelling of a solar PV generation scheme in a single order transfer-function domain in a linear approach for control zone one is available [16].

The outline of the paper includes the following:

- To study the mathematical balance model of coal-based power generation and load in the linear domain for control zone two. The control zones (two) are connected through the AC tie-line and, finally, come out into an interconnected arrangement for frequency normalization studies.

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- To design the auxiliary control action built on the concept of FL, which is FL built proportional control, FL built integral control, and FL built PI to achieve the required frequency for variable loading conditions.
- The performance of all FL control efforts is to check on the PV-Thermal linked system for variation in load demand, and the results, as well as analysis of frequency normalization studies, are shown to justify the advancement of present work.

II. FL Design Built on Proportional-Integral (PI) FLC

A nonlinear PI FLC can be developed by taking both 'area control error' and 'Integral of area control error' as the inputs. The 'area control error' and 'integral of area control error' are divided into five zones: negative Big, Negative Small, Zero Error, Positive Small, and Positive Big. The membership function is chosen as triangular and all symmetrical. The output of the controller is fuzzified into five zones Positive Big, Positive Small, Zero Error, Negative Small, and Negative Big. The design rules used for two-input PI FLC are given in Table-I, and for two sets of input, which are ACE and integration of ACE, the 25 possible sets of rules are formed to achieve required action for interconnected PV-Thermal system.

TABLE I. Rule base for Fuzzy PI for LFC of PV-Thermal System

		ACE				
		NB	***NS***	***ZE***	***PS***	***PB***
∫(ACE) dt	***NB***	NB	NB	NS	NS	ZE
	NB	NB	NB	NS	NS	ZE
	NS	NB	NS	NS	ZE	PS
	ZE	NS	NS	ZE	PS	PS
	PS	NS	ZE	PS	PB	PB
	PB	ZE	PS	PB	PB	PB

The FL with which the rules are formed is those of Zadeh. If μA and μB represent the grades of membership of an object in fuzzy set A and B, respectively, then this logic defines

$$\text{AND}\ (\mu_A, \mu_B) \cong \min\ (\mu_A, \mu_B) \quad (6)$$

$$\text{OR}\ (\mu_A, \mu_B) \cong \text{Max}\ (\mu_A, \mu_B) \quad (7)$$

Finally, the Mamdani's (min-max) inference method is used for different rules for a set of input. Finally, the defuzzification method is used to get the crisp value of the output of the controller for a set of input to the PI control. The Centroid method is used for defuzzification and also known as the center of area or center of gravity. This method is one of the most prevalent and physically appealing defuzzification methods. The relation to determining the crisp value of the output is as follows;

$$\Delta U = \frac{\int \mu_0(u)u\,du}{\int \mu_0(u)\,du} \quad (8)$$

III. FL design built on proportional FLC

Proportional control action using FL can be obtained by taking into consideration only 'area control error (ACE)' at every sampling instant of the controller. The area control error and incremental output of the controller are fuzzified into five zones in order to achieve proportional FL action. Following rules are used for obtaining the characteristics of a proportional FLC;

TABLE II. Rule base for Proportional FLC

R1	IF AĈE is PB THEN, ΔPc is PB
R2	IF AĈE is PS THEN, ΔPc is PS
R3	IF AĈE is ZE THEN, ΔPc is ZE
R4	IF AĈE is NS THEN, ΔPc is NS
R5	IF AĈE is NB THEN ΔPc is NB

IV. FL design built on integral FLC

Integral control action using FL can be obtained by taking into consideration the integrate of area control error at every sampling instant. The area control error is the input to the FLC, and the output of the controller is the crisp value of the incremental output after fuzzification. Then, the real change in output is obtained after the defuzzification of the values. Following rules are used to get the integral control action;

TABLE III. Rule base for Integral FLC

R1	IF ACE is NB THEN, ΔPc is PB
R2	IF ACE is NM THEN, ΔPc is PM
R3	IF ACE is NS THEN, ΔPc is PS
R4	IF ACE is PS THEN, ΔPc is NS
R5	IF ACE is PM THEN, ΔPc is NM
R6	IF ACE is PB THEN, ΔPc is NB

V. Simulation Results & Analysis

The present investigation is to deliberate the possible examination of power generation and grid integration of PV to well establish plants having thermal power generation framework coming into an interconnected system and playing a dynamic part in managing the balance between generation and load cost-effectively. The connectivity is a plan to take into account the variable load frequency and tie-power deviation in PV control or thermal control regions. The two control areas, one with PV and another with the thermal founded generation, are connected through implies of AC tie-line.

The different modes of proportional, integral, and proportional-integral control are initiated in respective zones in the arrangement. This restores the tie-line deviation and frequency control variances to the original magnitude under a conceivable period (second). The objective of auxiliary control is to realize the frequency, tie-power deviations, and ACEs of each control zones with least overshoot, slightest settling time & satisfactory system responses for each control zones.

Earlier, the control efforts were design on the basis of conventional control way in order to achieve the standards of the system. However, conventional approaches are time-consuming and entirely unacceptable for different operating conditions. Hence, the concept of FL is used to design the control efforts for the linked PV-Thermal system. These are proportional FL, Integral FL, and FL action put in place to achieve the complete efforts and known as FL built PI for linked PV-Thermal System.

In order to achieve the proportional FLC, the error, which is ACE of different control zones are input to the FL action. Hence for proper fuzzification and to obtain a proportional response from FL, the input is divided into five zones, which are PB, PS, ZE, NS, NB; the output is also divided into five zones considering triangular membership function. The design set of rule base is given in Table II to achieve the integral action from FL; the ACE is integrated and input to FL. To obtain FL base integral action, the ACE is divided into six zones, which are NB, NM, NS, PS, PM, PB, and the output of FL is also divided into six zones with triangular membership function chosen for FL. This is due to simplicity and symmetry. The complete set of rule bases for integral FLC is given in Table III.

Finally, to obtain the complete efforts for the linked PV-Thermal system, the error and integration of error, which is ACE and integrate of ACE is used as input to PI built FL. The input ACE and integral of ACE are divided into NB, NS, ZE, PS, and PB, and the output of FL is also divided into five zones with triangular membership function for inputs and output of PI built FL. For two inputs and one output from FL, the total 25 possible combinations are possible, and that is why PI built FL has a set of 25 rules for linked PV-Thermal system. The complete rule base is given in Table I. The output is defuzzified through the centroid method in order to convert the crisp value to real values and input to the PV as well as thermal power to change the generation as per change in load demand. Finally, the performance of all design FL is tested on a linked PV-Thermal system for a 2% load change in the thermal control zone. The comparative analysis of all FL is carried out with respect to of responses for frequency, tie-power, and ACE alteration. These responses, which are obtained via all FL, are shown in Figures 2 (a-e).

The results show that proportional FL action has lower overshoot for tie-power alteration, frequency, and ACEs of the two control zones for load change in the thermal control zone, and also, the output is free from oscillations entirely. However, still, the error exists between the required and actual output of the system from proportional FL based action. On the other side, the response of integral FL has sustain oscillations, and oscillations exist in responses for 50 seconds also for PV as well as for thermal control zones and for other responses also. The overshoot of integral FL is also higher with regards to proportional FL. However, due to integral control efforts obtain via FL the all system responses reach back to steady-state value quickly. With regards to proportional FL and integral FL, the responses of tie-power, frequency, and ACE alteration of the two areas are much better in all aspects of system output obtain via PI built FL.

The overshoot is very less with regards to other FL actions as well as the responses of all outputs are free from oscillations. Further, all system responses reach back to their original values within 10 seconds only, which is highly required in frequency normalization of linked PV-thermal system. Thus it clearly shows that out of all FL action, the fuzzy PI can quickly set the balance between generation and load alteration and hence to limit the frequency normalization in the best possible time.

From the results, it is observed that the overshoot crest is tall for the frequency alteration of the PV zone (-0.06 Hz) when compared to the frequency dip (-0.04 Hz) for thermal control zone, despite the load alteration in the thermal control zone of linked PV-thermal system. The settling time is additionally lower in thermal control when compared to PV.

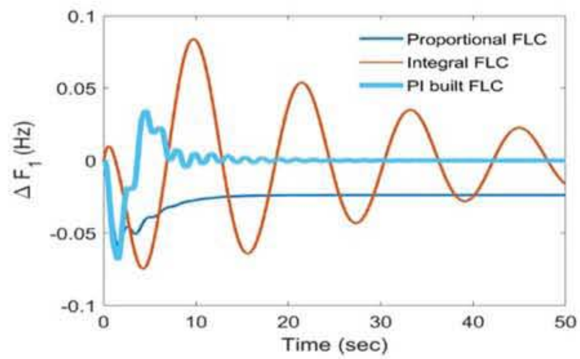


Figure 2. System results for step load disturbance in area-2 (a)

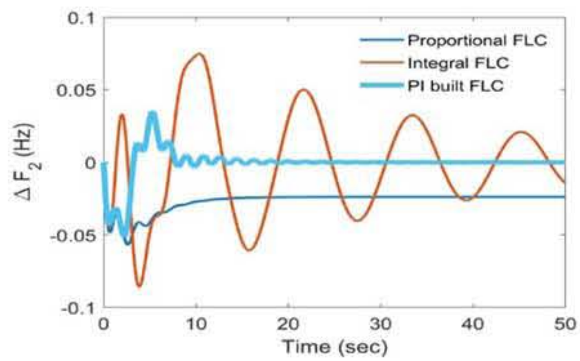


Figure 2. System results for step load disturbance in area-2 (b)

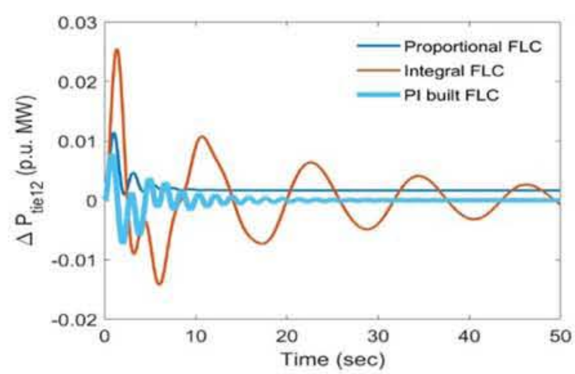


Figure 2. System results for step load disturbance in area-2 (c)

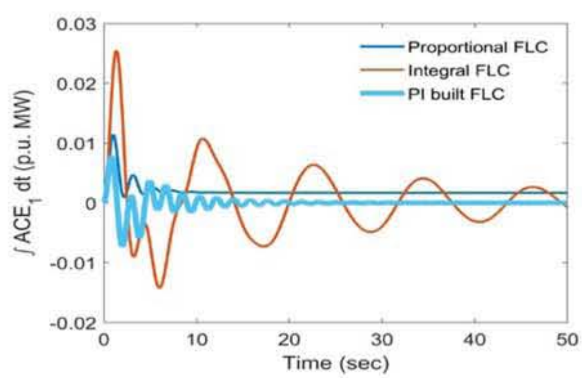
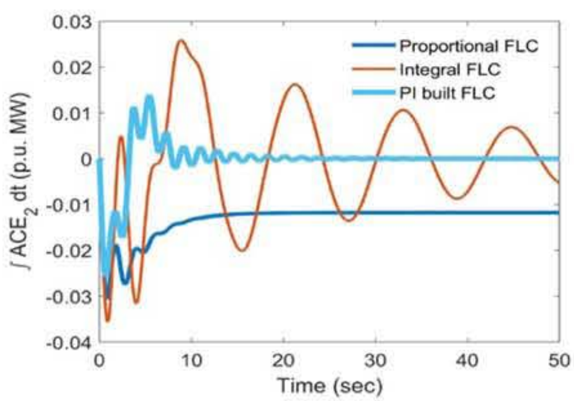


Figure 2. System results for step load disturbance in area-2 (d)



(e)

Figure 2. System results for step load disturbance in area-2 (e)

The framework reactions may get awful more in case a variation of the load is examined at the PV zone in comparison to the thermal control zone. This can be due to the reality that thermal control plants are steadier and unbending control plants when compared with the PV control under varying loads.

VI. Conclusion

This work considers the viability of PV integration to conventional thermal plants interconnected through the AC tie-line. The study involves the frequency normalization of the interlinked PV-Thermal control zones under varying loads. Various approaches, such as proportional, integral, and proportional-integral control built on FL, are initiated for each control zones for frequency normalization studies. The objective of auxiliary controllers is to realize the frequency, tie-power deviations, and ACEs of each control zones with least overshoot, slightest settling time & satisfactory system responses for each control zones for a specific change in loading conditions in linked PV-Thermal system. The results of all framework reveal that PI built FLC is speedy sufficient to bring back the framework results to unique esteem in the least time with decreased, to begin with, top and high damping in comparison to that seen by others FL actions. Also, to begin with, top of frequency alteration in the PV control produced range is more significant compared with the thermal control region. As a result, the thermal control zone has better performance under varying loads due to more substantial settling time and compliance with satisfactory limits.

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