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Solar photovoltaic integrated load frequency control of power system using variable structure fuzzy controller

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ABSTRACT

The incorporation of renewable energy sources into modern power systems is on the upswing, intending to produce and deliver cost-efficient electricity to meet the ever-increasing demands of today's world. Solar energy stands out as a plentiful and robust solution for meeting current electricity requirements. However, integrating solar photovoltaic (PV) generated power into the contemporary power system introduces complexity, necessitating the development of suitable control design to ensure effective regulation of load frequency control (LFC). This research paper concentrates on the mathematical modeling and integration of solar PV generated electricity into a hydrothermal system. In addition, this study also evaluates the performance of the variable structure fuzzy (VSF) control with reduced rule base for hydrothermal system concerning varying degrees of disturbances in one or in both regions of the power system. Moreover, the research reveals that the integration of PV power into hydro-thermal systems can improve the LFC outputs and mitigate system deviations in the face of different disturbance scenarios.

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1. INTRODUCTION

In current trends, the primary emphasis within the electrical industry is centered on providing cost-efficient and dependable electricity while satisfying consumers reasonable quality standards. Moreover, the rising demand for electrical power poses difficulties in maintaining a delicate equilibrium between power generation and consumption. Achieving this balance within the power system can be accomplished by employing strategies that actively manage both active and reactive power. Reactive power control oversees managing the voltage profile, while active power generation, aligned with active power demand, dictates the frequency profile of the system, thereby guaranteeing the provision of top-quality energy to end-users. In modern power systems, the essential procedures for controlling voltage and frequency are executed by employing automatic voltage regulators (AVRs) and load frequency control (LFC) regulators installed on power generators. The primary goal of LFC is to reduce deviations in frequency and fluctuations in inter-area tie-line power to levels deemed acceptable, which helps manage shifts in demand and disturbances [1], [2]. LFC has garnered significant attention from researchers who are consistently delving into comprehensive control designs to maintain frequency and tie-line power within allowable thresholds. This continuous research endeavor seeks to offer a simple and effective control solution for addressing this issue. Initially, the focus in this field was on control design using traditional methods. However, these conventional control techniques fell short in delivering the required performance across various operating conditions within the energy system. Consequently, the development of design and control strategies for LFC has progressed, leading to the adoption of numerous control designs aimed at addressing LFC challenges. Researchers and power engineers have successfully employed a variety of approaches in LFC design, encompassing robust control [3], [4], decentralized control in various areas of power system is discussed in paper [5]–[7], optimal control and dynamic performance of a two interconnected power system consisting of hydropower plant is demonstrated in paper [8], [9]. Sharma *et al*. [10], have presented the design of optimal output feedback automatic generator control (AGC) regulation of an interconnected power system. A comprehensive literature on variable structure control (VSC) is discussed in [11]. The VSC design can offer the qualities of proportional and integral controller and may aimed to solve the LFC issues. However, finding the optimal gains of proportional and integral controller is a time consuming and challenging process and that is why it is not advisable to use this design as it is. Further, there has been a significant exploration into the application of fuzzy logic techniques for addressing operational and control challenges in real power systems [12]–[17]. Govindaraju *et al.* [12], utilized an adaptive fuzzy approach to determine the gains of traditional proportional-integral (PI) controllers, using information derived from the area control error (ACE). A robust LFC design that accounted for system non-linearity and parametric variations, achieved through the use of the Takagi-Sugeno fuzzy system was demonstrated [13]. The output tracking excitation control solution for electric power system generators, employing adaptive fuzzy logic was proposed and tested in [14]. Furthermore, Anand *et al.* [15] proposed a nonlinear type-2 fuzzy-based design that takes into consideration the LFC non-linearities to enhance LFC performance. The fuzzy gain scheduling technique based on optimization techniques for multi-area system was discussed in [16]. A hybrid neuro fuzzy oriented LFC for a deregulated environment was presented in [17]. Based on the aforementioned research findings, it is evident that the LFC issue can be effectively addressed by incorporating fuzzy logic in conjunction with VSC. This approach yields a zaQW (VSF) control design that operates in a proportional and integral mode, utilizing a simplified and more concise set of rules for tuning. As the focus on renewable energy sources continues to grow, the LFC problem has also evolved over the past few decades, incorporating photovoltaic (PV) systems into traditional LFC models. Consequently, PV generators are now actively contributing to the system's frequency response by injecting active power, ultimately achieving a balance between generation and the system's load demand, and hence providing quick and improved LFC responses [18]–[22]. The implicit Euler solver for interconnected areas of LFC is emphasized in paper [23], [24]. This paper aims to implement a VSF for PV grid integrated LFC to enhance the power system's reliability and quality to resolve the uncertainties associated with PV grid. In addition, VSF with a lower rule base is designed and implemented to match energy generations with the load demand with and without the integration of solar PV into LFC of the system.

2. INVESTIGATED MODEL

For the present research work, a thermal power plant interlinked to hydropower plants via means of alternating current (AC) tie-line is used for the investigation. For supplementary electric power and energy sustainability, PV-based power generating model is integrated into each control area of LFC on the investigated model shown in Figure 1 (in Appendix). Gain parameters of the proportional-integral derivative (PID) controller have been tuned based on VSF for better dynamic response and control system robustness. The standard parameters depicted in Table 1 in this section have been considered in this study. Furthermore, VSF is aimed at maintaining zero steady-state error in the power system. MATLAB software is used to conduct this investigation. In addition, VSF will adjust the control parameters dynamically based on real-time conditions of power system by considering the intermittent nature of the PV grid.

Table 1. Parameters for two interconnected areas of power system

Area	Parameters	Definition	Value
Area 1, thermal power plant	$\tau_G(s)$	Generator time constant	0.08
	$\tau_T(s)$	Turbine time constant	10
	τ_R	Reheater time constant	0.3
	τ_P	Generator time constant	20
	K_P	Gain constant	120
	R	Droop	2.4
Area 2, hydro power plant	$\tau_G(s)$	Generator time constant	0.6
	$\tau_T(s)$	Turbine time constant	32
	τ_R	Reheater time constant	0.5
	τ_P	Generator time constant	3.76
	K_P	Gain constant	20
	R	Droop	3.0

3. MODELLING OF PV SYSTEM FOR LFC

Incorporating a PV array into a LFC power system necessitates a strong grasp of power electronics principles and strict adherence to established guidelines [18], [19]. Once the power output from the PV array is acquired, the initial step in linking it with the LFC power system involves the utilization of a boost converter. This device raises the voltage to a suitable level, preparing it for use as the input in the subsequent stage, which is the inverter. The primary function of the inverter is to generate AC current to harmonize with the grid's AC power characteristics and synchronize with its voltage and current levels [18]. When connected to the grid, the input for the PV system comprises the direct current (DC) output from the PV array. This involves a system composed of 150 arrays, each capable of generating 30 kW of power, and these arrays are connected to a consistent voltage source of 6 kV on the PV array side [20]. The PV system operates at the lower end of the voltage and power spectrum, which is commonly found in inverter-based PV systems that are connected to grids with power capacities ranging from 1 kW to a few MW [21]. The maximum power point (MPP) represents the specific voltage value at which the highest output power is achieved, and it is a critical factor in solar array performance [22], [25]. In this particular configuration of solar arrays, the MPP is located at which results in an MPP of 4.5 MW. The output generated by an array is inherently DC. When observed over longer time periods, such as hours, this output exhibits nonlinear behavior. However, when analyzed within shorter intervals, typically seconds (the relevant timeframe for designing system controllers), it manifests as a stable, constant DC voltage. Even in practical scenarios where voltage variations occur over extended periods due to factors like temperature fluctuations or changes in solar irradiance, these variations shift from one consistent DC value to another. At first, the PV system can be linked to conventional power system with the utilization of a DC-DC boost converter to connect the PV system to the grid. In an ideal scenario, this converter essentially acts as an amplifier or gain device. To determine this required gain, it becomes crucial to understand the overall gain needed between the DC voltage and the desired amplitude of the final AC voltage, denoted as 'm' in (1):

$$m = \frac{V_{dc}}{V_{ac}} \quad (1)$$

In this model, an optimal value for 'm' is considered to be 0.866 and in this specific instance, it has been set at 0.7. The PV system operates with a consistent DC voltage, while the output current and power of the PV arrays fluctuate due to variations in solar irradiance and temperature. With this fixed DC voltage value and the selected 'm' value for this particular system, the amplitude of the AC voltage remains constant. Consequently, the AC and power can vary in sync with changing conditions. Now, we can employ the value of 'm' to determine the required voltage after the boost converter, denoted as 'V_2' in the equation. Further, the PV system is connected to the low-voltage side of the grid, and the root mean square (RMS) value of the grid line voltage in the conventional system under consideration is 11 kV. This implies that the grid phase voltage is 6.4 kV. We will use this value because in this PV system, only one phase (phase A) is taken into account, even though there are two other phases (B and C) contributing power to the system with a certain phase shift.

$$V_2 = \frac{V_m}{m} = \frac{6.4kV}{0.7} = 9.1\ kV \quad (2)$$

Hence, we can compute the gain of the boost converter as (3):

$$M_1 = \frac{V_2}{V_1} = \frac{9.1}{6} = 1.52 \quad (3)$$

Therefore, the boost converter gain will be computed as (4):

$$G_1 = \frac{1}{M_1} = \frac{1}{1.52} = 0.66 \quad (4)$$

The subsequent step involves the DC-AC inverter, which transforms the DC into AC suitable for connection to the conventional AC-based power system. The transfer function can be derived by performing the Laplace transform on each term. Since AC is given by:

$$i_{ac} = I_m\, cos(\omega t) \quad (5)$$

Laplace transform for (5) is given by:

$$\frac{s}{s^2+\omega^2} \quad (6)$$

The output current of the boost converter which is I_2, has a Laplace transform of $\frac{1}{s}$. Since the second tranfer function is inverting DC to AC, then (7) is expressed as (7):

$$G_2(s) = \frac{i_{ac}(s)}{I_2(s)} \quad (7)$$

By substituting (7) into (6), we obtain:

$$G_2(s) = \frac{\frac{s}{s^2+\omega^2}}{\frac{1}{s}} \quad (8)$$

Finally, (8) can be formalized to:

$$G_2(s) = \frac{s^2}{s^2+\omega^2} \quad (9)$$

The angular frequency (ω), is given by $2\pi.50Hz$ which result updating (9) to:

$$G_2(s) = \frac{s^2}{s^2+98700} \quad (10)$$

The third transfer function aims to convert (I_2) into instantaneous power so that the output of the conventional system will match, since the energy from PV to power grid should be in terms of power. The gain is:

$$G_3 = \frac{p}{i_{ac}} \quad (11)$$

Then the instantaneous power is given by:

$$p = {i_{ac}}^2.Z_m G_3 = \frac{p}{i_{ac}} \quad (12)$$

The impedance of a purely resistive load can be expressed as (13):

$$p = \frac{V_m}{I_m}.{i_{ac}}^2 \quad (13)$$

Apply (5) to (13):

$$p = \frac{V_m}{I_m}[I_m\, cos(\omega t)]^2 \quad (14)$$

By applying Laplace transform in (14), we obtain:

$$p(s) = \frac{V_m I_m}{2s} + \frac{V_m I_m}{2}\left(\frac{s}{s^2+2\omega^2}\right) \quad (15)$$

Substitute (15) into (11):

$$G_3(s) = \frac{p(s)}{i_{ac}(s)} = \frac{\frac{V_m I_m}{2s}}{I_m \cos\omega t} + \frac{V_m I_m}{2}\left(\frac{s}{s^2+2\omega^2}\right) \quad (16)$$

From (16) may be rewritten as (17):

$$G_3(s) = \frac{(s^2+\omega^2)(s^2+4\omega^2)}{s^2(s^2+16\omega^2)} \quad (17)$$

From (3.10), $\omega = 2\pi.50 = 314.16$ rad/sec, the third transfer function which is capable to convert AC into instantaneous power is given by (18).

$$G_3(s) = \frac{6351s^4+1.88e9s^2+1.237e14s^2}{s^4+3.948e5s^2} \quad (18)$$

By squared the inverted current in (12) to determine the instantaneous power, the frequency of the PV get doubled as seen in (18). The fourth transfer function of the PV is to transform the instantaneous power that was in frequency domain into average power in time domain. The gain is given by.

$$G_4 = \frac{P_{ave}}{p} \quad (19)$$

The average power is expressed as (20):

$$P_{ave} = \frac{1}{T}\int_0^T v_{ac}.\, i_{ac} dt \quad (20)$$

Apply (5) to (20), both voltage and current. Then (20) will be expressed as (21):

$$P_{ave} = \frac{1}{T}\int_0^T V_m \cos(\omega t).\, I_m \cos(\omega t) dt \quad (21)$$

Apply (15) into (21) and consider Laplace transform. We obtain:

$$G_4(s) = \frac{P_{ave}(s)}{p(s)} = \frac{V_m I_m}{2} \div \left(\frac{V_m I_m}{2s} + \frac{V_m I_m}{2}.\frac{s}{s^2+2\omega^2}\right) \quad (22)$$

To obtain a transfer fuction that convert the instantaneous power to average power, use the same method used to obtain the $G_3(s)$.

$$G_4(s) = \frac{s^2+3.948e5}{2s^2+3.948e5} \quad (23)$$

4. DETAILED MODELLING OF VSF AND RESULT ANALYSIS

The performance of hydrothermal LFC can be realized through the adoption of the fuzzy with variable structure concept. As per this structure, the designed controller has the power to operate as proportional controller at one time and executes as integral controller later utilizing fuzzy tuning methods to swiftly reduce LFC deviations of hydrothermal system for a step disturbance in one area or in both areas. As a result, the control strategy dynamically responds to the current system error, with the dual structure relying on fuzzy techniques to modify controller constraints, fine-tuning gains through fuzzy logic systems across two operational modes. The schematic model of VSF is given in Figure 2.

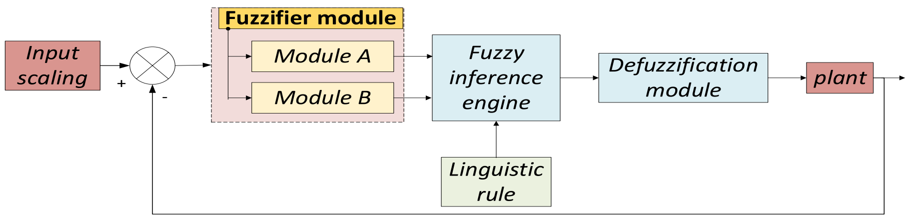

Figure 2. Block diagram of a VSF

The proposed methodology can be broken down into three key stages: (a) allocating inputs to control zones and converting real values into crisp values, (b) improving the fuzzy rules for the proportional and integral controller action with few rules, and (c) transforming fuzzy values into real values through a process known as defuzzification. In order to determine the appropriate action through the proposed control approach, the error is categorized into four segments: positive large (PL), positive small (PS), negative large (NL), and negative small (NS). Similarly, for achieving optimal integral operation, the error is divided into categories such as negative big (NB), negative medium (NM), NS, PS, positive medium (PM), and positive big (PB). The rules formulated for proportional and integral fuzzy action (IFA) is as follows.

Tuning rules for propotional fuzzy action (PFA):
- If error (E) is PL then PFA is NL
- If E is PS then PFA is NS
- If E is NL then PFA is PL
- If E is NS then PFA is PS

Tuning rules for IFA:
- If E is NB then IFA is PB
- If E is NM then IFA is PM
- If E is NS then IFA is PS
- If E is PS then IFA is NS
- If E is PM then IFA is NM
- If E is PB then IFA is NB

In section 3, a comprehensive, step-by-step explanation of the mathematical modeling of PV systems for LFC in transfer function mode is provided. Subsequently, a VSF controller is meticulously designed and seamlessly integrated into the hydrothermal model to facilitate LFC. The system's response is assessed under a load disturbance of 0.01 per unit (p.u.) introduced into the thermal system, and the outcomes are vividly illustrated in Figure 3. The findings reveal that all essential system parameters swiftly return to their reference values within a matter of seconds. Initially, the VSF controller employs proportional control action, effectively mitigating the initial peak in system responses. As the system responses stabilize, the VSF controller seamlessly transitions to integral action, minimizing the error between the actual and desired responses. A comparative analysis of the outcomes of the VSF controller with and without PV integration underscores the significant benefits of PV integration. It notably reduces overshoot and accelerates the settling time for all LFC responses in the hydrothermal system. Furthermore, PV integration leads to a reduction in oscillations within the system responses, ultimately elevating the performance of the VSF controller under similar operational conditions.

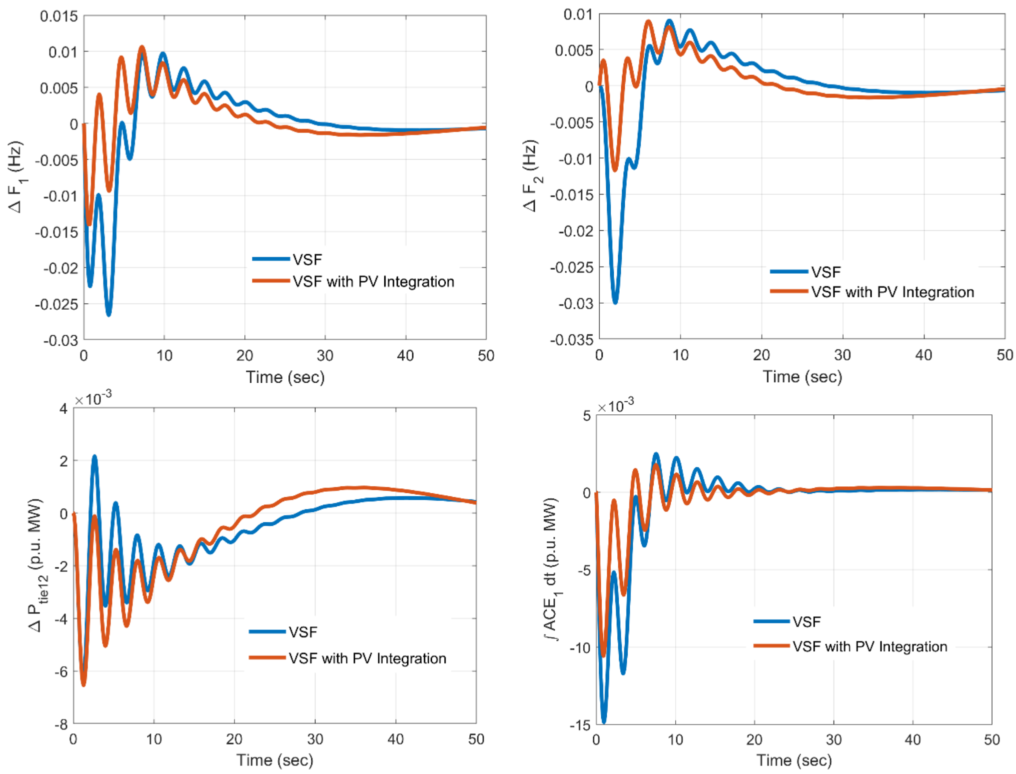

Figure 3. LFC outcomes of hydro-thermal model for 0.01 p.u. load change in thermal system

The study's scope is extended to the LFC of the hydrothermal system by introducing a load alteration of 0.01 p.u. in the thermal system and a 0.005 p.u. load alteration in the hydro system. The responses of the LFC system under these conditions are depicted in Figure 4. When comparing the outcomes of the VSF controller for LFC with and without PV integration in a similar operational context, it becomes evident that simultaneous disturbances in both areas lead to increased overshoot and prolonged settling times for all LFC responses. However, the integration of PV with VSF exhibits reduced overshoot, improved settling times, and no steady-state error in all LFC responses. This advantage arises from PV's ability to rapidly supply the required active power, aligning electrical energy generation with the current load demand. Furthermore, it's worth noting that the frequency deviation in the hydro system is notably higher than in the thermal system. Nevertheless, VSF with PV integration effectively manages to achieve improved LFC results, enhancing the overall performance of the system.

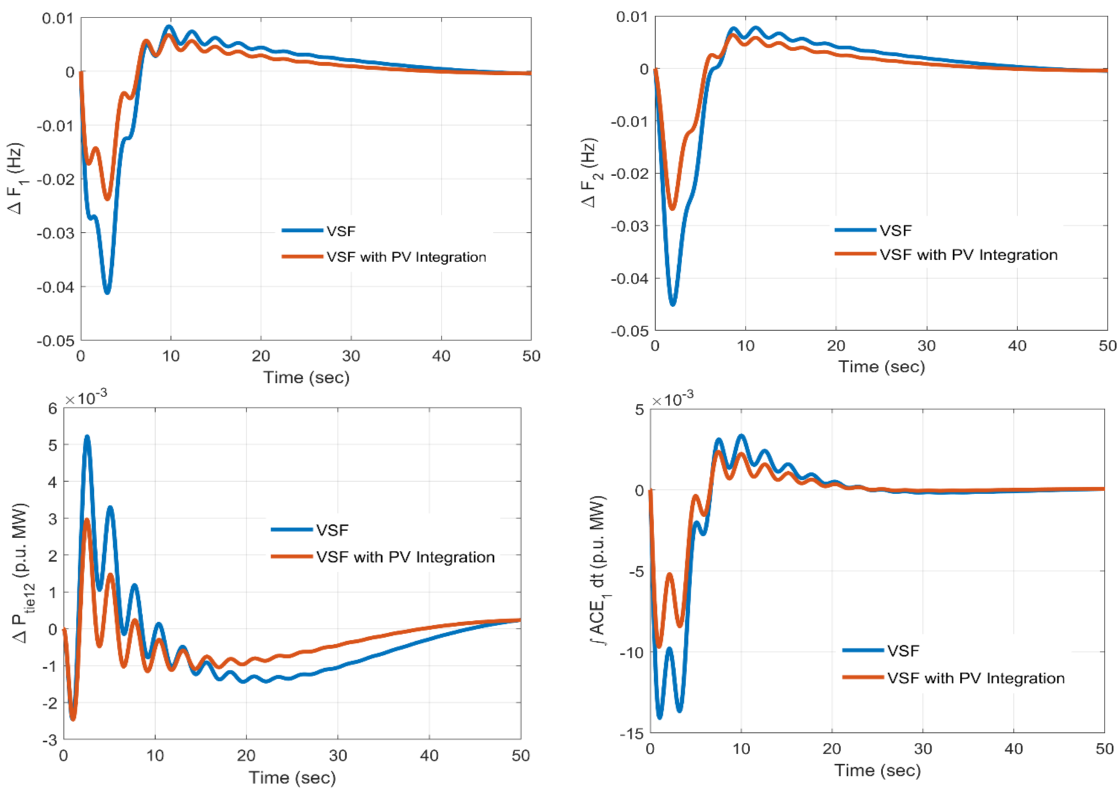

Figure 4. LFC outcomes for 0.01 p.u. load alteration in thermal and 0.005 p.u. load alteration in hydro system

5. CONCLUSION

The primary objective of this study is to create a mathematical model for PV systems within the context of LFC in a hydrothermal power generation system. The aim is to assess how the integration of PV technology into the hydrothermal system can reduce the disparities between electricity generation and the demand, subsequently minimizing deviations in LFC. Moreover, we employ the concept of variable structure feedback to attain LFC objectives with minimal overshoot, quicker settling times, and the achievement of stable steady-state conditions for all LFC outcomes. The performance of LFC is evaluated by subjecting the model to step changes in load, which are interconnected through AC tie-lines. The results of VSF oriented LFC with and without PV integration are matched, and our findings reveal that integrating PV into each control area leads to improved time responses for various system states during LFC, whether it's due to disturbances in one area or simultaneous disturbances in both areas of the system.

APPENDIX

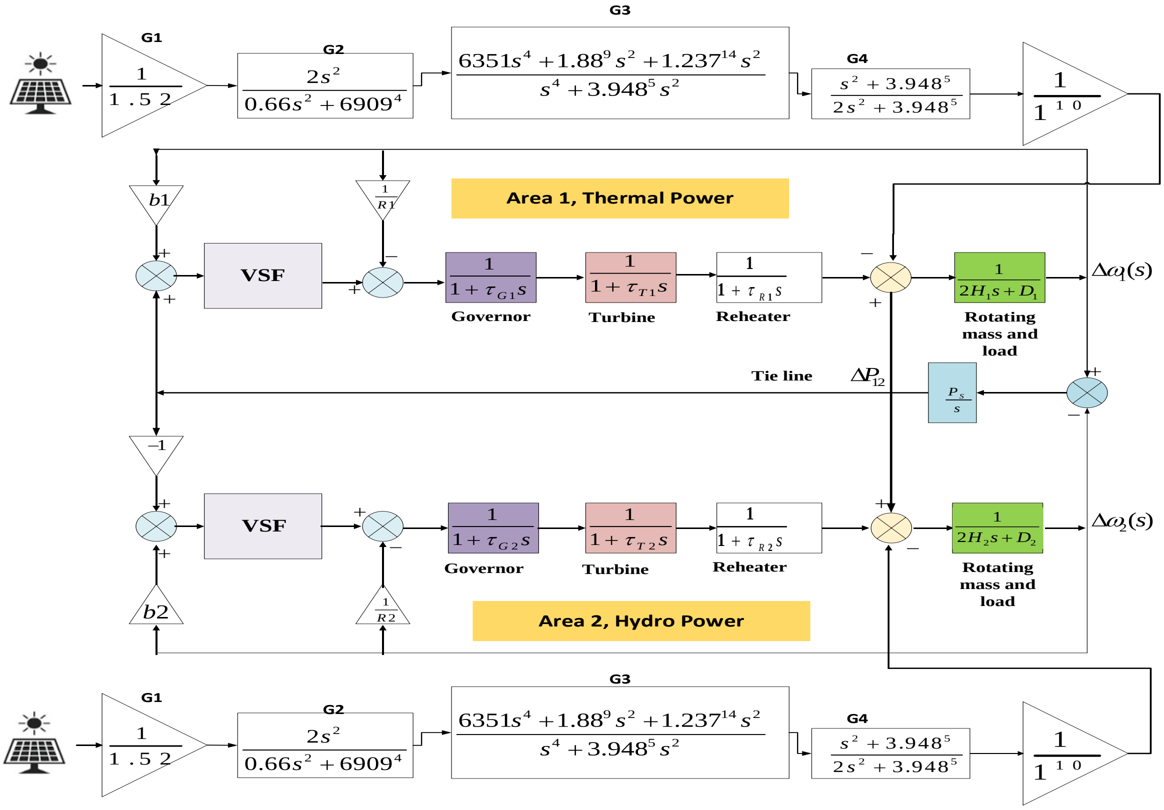

Figure 1. LFC model with PV integrated to each area of hydro-thermal system

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