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Frequency Regulation in Presence of PV-generation using Robust Control Theory

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ABSTRACT

Inevitable energy oscillations due to presence of renewable energies cause frequency variation in smart grids. This paper suggests a novel load-frequency control method based on robust control theory. Proposed controller regulates the frequency of the system by giving proper order to thermal units and determine the amount of their generated power to compensate PV power oscillations. This method applied to a five-bus system, including a PV generation and three typical thermal units. The validity of this method evaluated by computer simulation analyses using MATLAB Simulink.
Keywords: Frequency regulation, Robust Control Theory, frequency control, PV generation.

INTRODUCTION

Today solar and wind energy systems are two main choices for green power generation. Most of recent researches directed to the impact of wind power and PV Generation on system frequency. Today's power system operations require reconsideration for system instability and control problems. It is vital to provide more effective and robust control strategies in order to achieve a new trade-off between system security, efficiency and dynamic robustness. The increasing number of major power grid blackouts that has been experienced in recent years [1-3], confirms this fact, and shows that classic control needs an update in terms of control methods. Modern power system is not working as old times. Operation in new grid environment will certainly be more complex than the past, regarding to the considerable degree of interconnection, and the presence of technical and economic constraints (deriving by the open market) to be considered, together with the traditional requirements of system reliability and security [4]. On the other hand, in modern power systems the decentralized LFC problem is quite a challenge. Controllers based on Neural, fuzzy or genetic algorithms are so complicated and time consuming for find proper answer for the problem, these controllers are not capable on online controlling. In [5], the decentralized LFC problem is solved by using robust optimal PID controller for two-area power systems. In [6] there is a novel H_{∞} -based approach to integrate storage into frequency control. A nonlinear robust control theory to design the excitation controller used in [7] in order to realize the decentralized robust control and improve stability of the system. A robust analysis for decentralized load frequency control (LFC) for multi-area power systems studied and applied to a four-area power system and the results show that the method is convenient and useful [8].

The focus of this paper is on compensating active power. Today, PV-generation units are a serious problem for any power system commonly used all over the world. Many solutions have been proposed by power engineers, some of them based on predicting the amount of power generated by PV unit, and some other based on controlling power electronic inverters.

This paper suggests a new control method to determine the generated active power of a PV unit and thermal units simultaneously, in a way that the sum of their generated power stay constant at any moment. Simply stated, thermal unit generates in a way to compensate power oscillations of PV unit.

As Mentioned before, there is a serious need of upgrading control generation systems, especially load-frequency control system. In near future this upgrade will be necessary for every grid. Many solutions for this problem has been presented, but among them robust control has outstanding properties and many

advantages. In this study, a controller based on robust theory has been simulated and applied to thermal units, and PV generation unit. This novel controller applied to a 5-bus power system and expected the controller to decrease frequency variation effectively, and manage frequency in a fast, stable and punctual manner.

FREQUENCY CONTROL

The frequency of a power system is dependent on real power balance. A change in real power demand at one point of a network reflects on the system by a change in frequency. Significant interconnection frequency deviations can cause under/over frequency relaying and disconnect some loads and generations. Under unfavorable conditions, this may result in a cascading failure and system collapse[2]. Primary control action is not usually sufficient to restore the system frequency, especially in a smart grid, and the supplementary control loop is required to adjust the load reference set point through the speed-changer motor. Therefore, In addition to a primary frequency control, most large synchronous generators are equipped with a supplementary frequency control loop. This control system with primary and supplementary control loops called Load-Frequency loop (LFC) and its duty is to maintain frequency variations between desired boundaries [4]. LFC is a service related to the short-term balance of power and energy of the power systems. LFC was an ancillary service for the system but today it is an inevitable and one of the most profitable services for electricity trading, who not only provide better conditions for generation and loads, but also make it possible to manage more DGs in smart grid. Microgrid can operate in parallel to the grid or as an island. The most compelling feature of a microgrid is the ability to separate and isolate itself from the utility's distribution system unintentionally during events (i.e., faults, voltage collapses, black-outs) [9]

Compared to Voltage stability, there has been much less work on power system frequency control analysis and synthesis, while violation of frequency control requirements was known as a main reason for numerous power grid blackouts [4].

As mentioned in [10], LFC control design methodologies can be categorized as:

- Classical methods
- Adaptive and variable structure methods
- Robust control approaches
- Intelligent techniques
- Digital control schemes

This paper presents a control scheme based on robust control approaches. This controller has only one input, that is frequency variation (Δf) which belongs to related control area, and one output that is reference power (ΔP) that will apply to the complementary thermal unit. This ΔP determine the exact amount of active power that should be generated by thermal units so that Δf be minimized.

CONTROL AREA THEORY

In a huge and linked power system, local generation is responsible for local change in load. On the other hand, in a grid with DERs, it is wise to use nearby generations for regulation local supply and demand. It is best in these areas to have their own control unit, So that each area consisting of a group of generators and loads can regulate their own area. This strategy can help system stability by removing unnecessary responses of generating units. In other words, this scheme argues that usually there is no need for all of generators to respond changes of any load, instead, they responsible for their local loads mostly.

The frequency assumed to be the same all over a control area. A multi-area power system comprises areas that interconnected by high voltage transmission lines or tie lines. Measured frequency of each control area is an indicator for the mismatch power in the interconnection and not in the control area alone.

In power systems, each control area contains different kinds of uncertainties and disturbances due to changes in system parameters and characteristics, load variation, errors in modeling, linearizing and environmental conditions. The LFC system in each control area should control the interchange power with the other control areas as well as its local frequency. Therefore, described dynamic LFC system model should be modified by taking into account the tie-line power signal. For this purpose, consider Figure (1) that shows a power system with N-control areas. The power flow of the tie-line from area 1 to area 2 will be:

$$P_{tie,12} = \frac{V_1 V_2}{X_{12}} \sin(\delta_1 - \delta_2) \quad (1)$$

Where X_{12} is the tie-line reactance between areas 1 and 2; δ_1, δ_2 the power angles of equivalent machines of the areas 1 and 2 and V_1, V_2 are the voltages at equivalent machine's terminals of the areas 1 and 2.

To maintain frequency and power interchanges with neighbor areas, there should be a tie-line flow deviation to the frequency deviation in the supplementary feedback loop. A suitable linear combination of

frequency and tie-line power changes for area i known as the area control error (ACE_i). ACE has two components, one for its own parameters and one for neighboring control areas. In the dynamical operation of power systems, it is usually important to aim for decentralization of control to individual areas. This aim should coincide with the requirements for stability of the overall system. This generally accomplished by adding a tie-line flow deviation to the frequency deviation in the supplementary feedback loop. A suitable linear combination of frequency and tie-line power changes for area i known as the area control error (ACE_i).

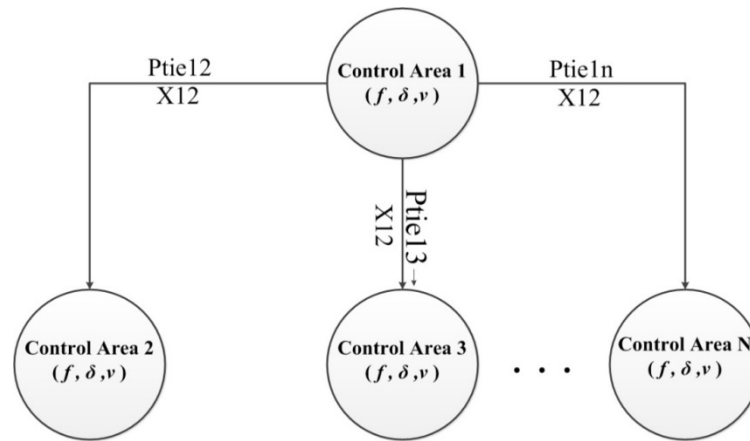


Figure (1) Different control areas in power system

ROBUST CONTROL THEORY

Parameters of the Existing classic LFC systems usually tune based on experiences. Today there is no doubt classic control is incapable of providing good dynamical performance over a wide range of operating conditions and various load scenarios. Therefore, novel modelling and control approaches are strongly required. This will help modern systems to obtain a new trade-off between market outcome and market dynamics. In this situation, the importance of robust control theory is deniable. Robust control theory not only has simple structure, but also has a fast response suitable for real time systems.

It may be noted that in the robust control approaches, the control objectives are to design load frequency controllers to not only meet the nominal stability and nominal performance requirements but also guarantee robust stability and robust performance [11] in power systems on the LFC problem.

A decentralized LFC based on H^∞ optimal control combined with an observer has appeared in [12]. The main feature of the robust decentralized scheme methods is reduction in the controller complexity and suitability for practical implementation. It is proven that H^∞ Robust control shows greater effectiveness for damping load disturbances over the conventional optimal control. The effectiveness of the proposed method investigated on 3-area networks involving thermal power plants and one PV generation unit, under load fluctuations. Closed-loop system via H^∞ control illustrated in Figure (2) A classic control system has similar structure. The main difference of proposed controller with classic control is that feedback loop value, or k , is a vector, which does not have constant value. Based on dynamic changes of the power system, k is changing every moment. Since mathematical concepts and formulations are extended, it is not proper to talk about them here. but in [4] there is a full review of robust control theory including H^∞ -SOF Control Theory. Also, there is more information in [13] And [14] about this theory.

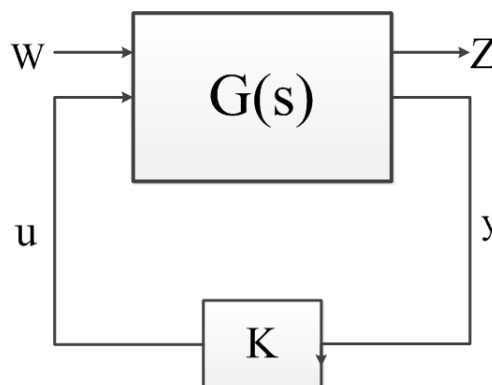


Figure (2) Closed-loop system via H^∞ control

By modeling generation system and considering a supplementary control loop, the result for a N-area control system will look like Figure (3) the details and steps leads to this model has been discussed in [15]. This loop is the main platform for the proposed control scheme. Above system can be modeled in Simulink and make use of it. As discussed before, the input of control system will be frequency deviation, and the output will be a reference power value as an order for generation units, and this means generation units take orders from proposed controller and the purpose is to smooth grid frequency.

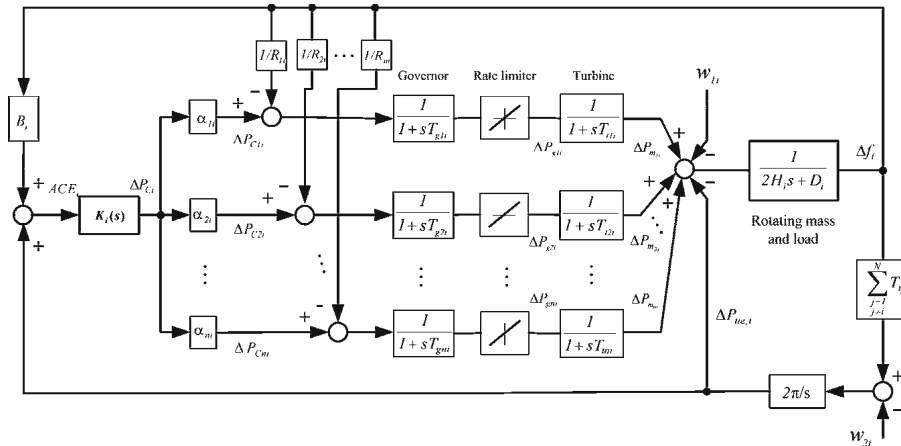


Figure (3) LFC system with different generation units and participation factors in area i

Structure of proposed controller

Controllers based on robust control theory are famous for their simplicity of structure and fast respond. General structure of proposed controller is based on mathematical model mentioned in [4]. Figure (4) illustrates this structure. There is two groups of inputs: W_i and U_i . W_i is a set of space-state variables belong to under control parameters (it is frequency here). U_i belongs to a feedback loop with variable gain that varies time to time. This gain is a matrix named K_i . Figure (5) shows a simulated sub-controller belongs to first control area; this controller uses Δf_2 and Δf_3 as main inputs. It should be noted that Δf_2 and Δf_3 are frequency deviations for second and third control areas, respectively. in Figure (6) there is LFC loop of first control area of under study system. This loop calculates Δf_1 . There is a similar LFC per each control area.

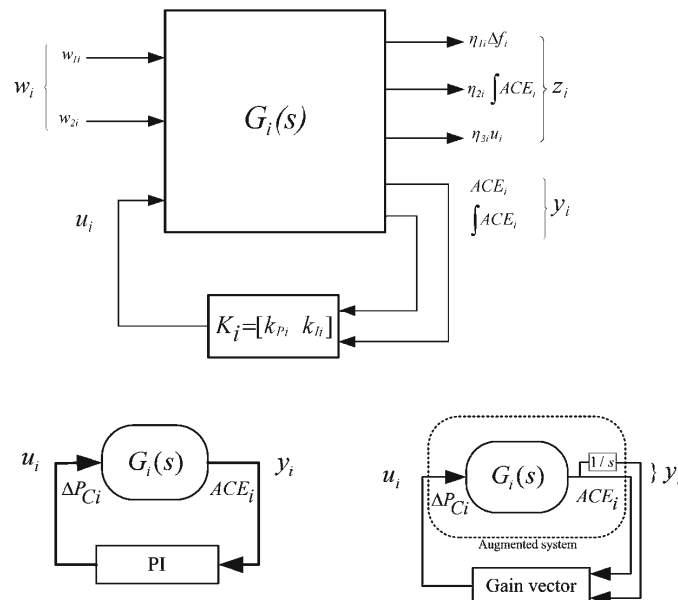


Figure (4) General structure of proposed controller

This controller has several advantage for example closed loop poles can be located in a prescribed region for achieving the required transient response and the resulting controller order is lower than the order of comparable Neural, fuzzy or genetic controllers. The Proposed control does not need centralized scheme. Because of its structure, it is applicable to a decentralized system with different control areas, so

privatization of the grid does not bother control strategy. The asymptotic stability of the overall power system for all admissible uncertainties was guaranteed.

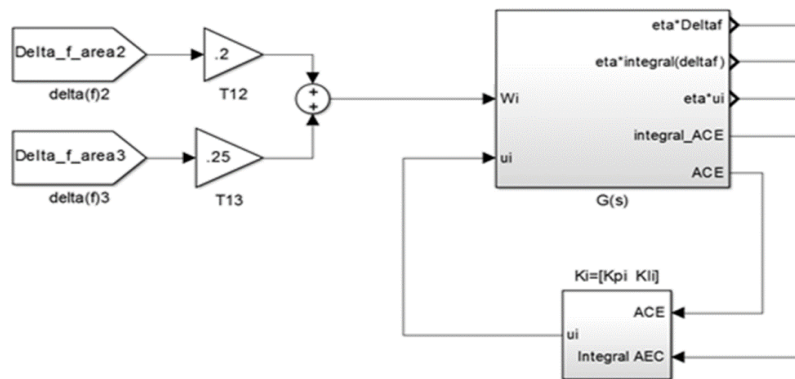


Figure (5) LFC system with different generation units and participation factors in area *i*

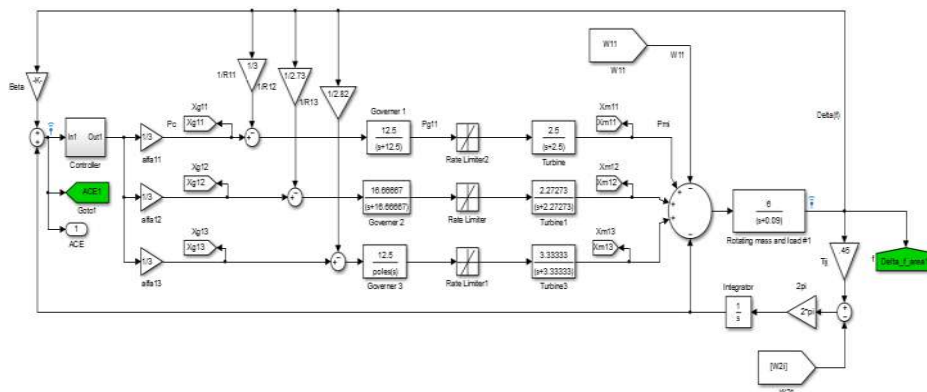


Figure (6) LFC loop for first control area

Photovoltaic generation unit

The sun is the largest energy source life while at the same time it is the ultimate source for most of renewable energy sources. Solar energy has several properties makes it fundamentally different from classic power sources: The available power is variable over time and involved with uncertainties. It is often varying randomly and not fully predictable. Today generation methods from solar energy can be categorized as:

- (i) photovoltaic panels (PVs)
- (ii) solar thermal collector
- (iii) Photovoltaic/Thermal Combi-panel [16]

As we know, today PVs are the most common technology among them. PVs are reliable, inexpensive, clean and have long life. PVs are shifting from being a negligible, often ridiculed, power generation technology to a mainstream source of power [17]. Although PVs faces the system with lots of problems; Firstly, PV generators connected to the grid by power electronic inverters. Consequently, they may introduce higher-order harmonics and, since they have no rotating masses, they cannot contribute inertia for dynamic support of power system stability. Secondly, as a modular technology, they mostly connected to the distribution grid or at the customer side of the grid. Consequently, they are usually not visible in the grid operators distribution management systems (DMSs). They generate reverse power flows in the distribution grid possibly causing overvoltage and their consecutive disconnection [17]. Many of recent researches currently directed to the impact of PV Generation on system frequency.

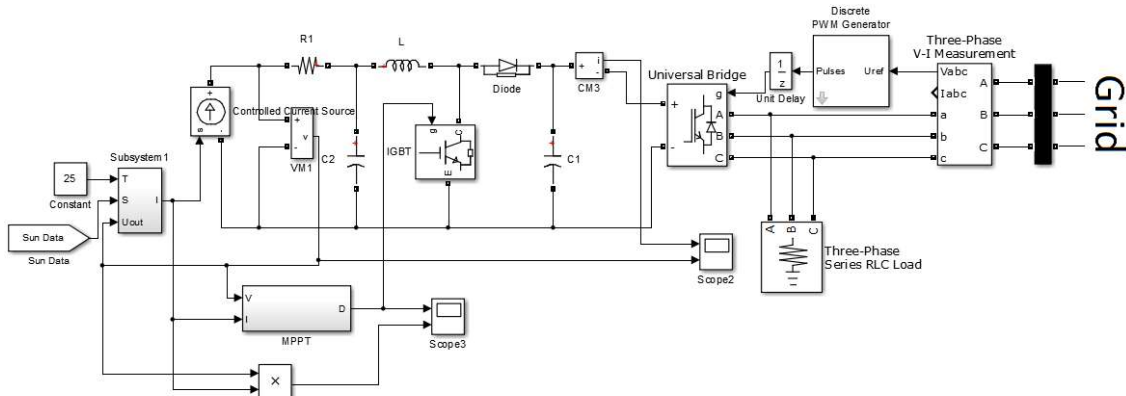


Figure (7) Grid connected PV system used in case study

In this study PV generation unit has been applied. Figure (7) Shows grid connected PV generation unit with variable sun radiation and constant ambient temperature. This unit connects to grid via a universal bridge. PV generation is proportional with sun radiation. Figure (8) shows real data for sun radiation in an ordinary day. In this figure, the time scale has been normalized to be usable for simulation conditions. This data belongs to a PV unit located in a desert village named Moaleman, located in Amirabad District, Damghan County, Semnan Province, Iran.

PV generation unit how brings a lot of power fluctuation to the grid. Figure (9) shows power generated and injected from PV to grid. This figure shows critical situation of power quality and the reason we insist on having robust control system.

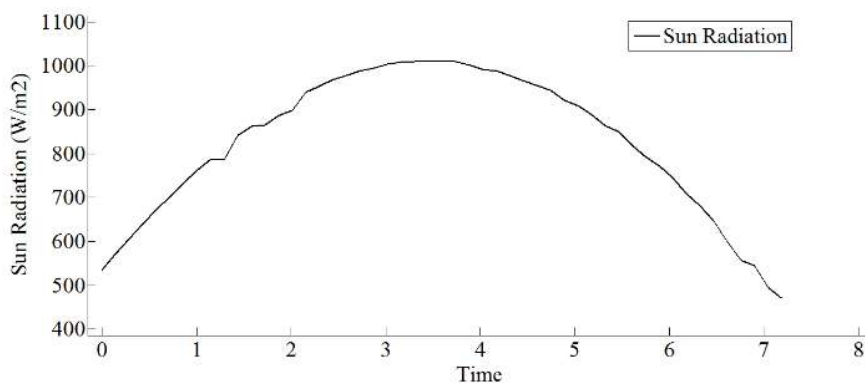


Figure (8) Grid connected PV system used in case study

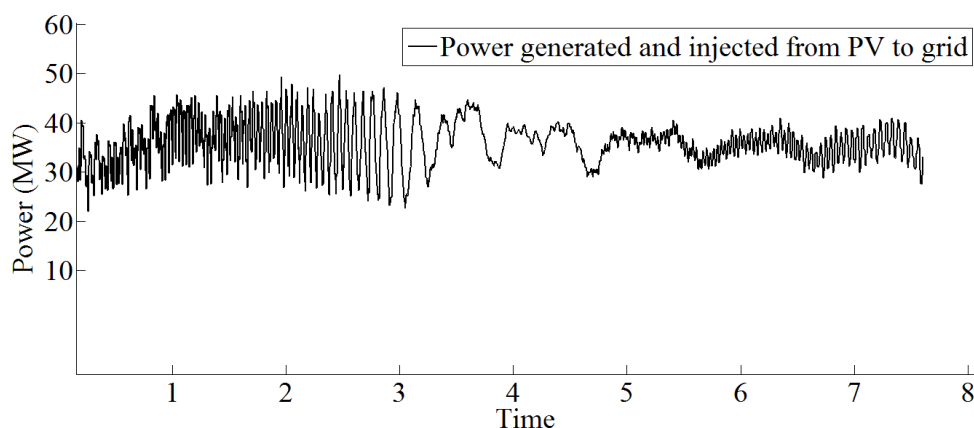


Figure (9) Grid connected PV system used in case study

Case study

Under study system in this paper is 5-bus power system with three control Area. Generation units are: one PV generation and three thermal units. The nominal power of these generation units are listed in table 1. Also, Figure (10) shows the model configuration of this power system. Nominal frequency assumed 50 Hz,

and nominal voltage for all buses is equal to 230kv. This system has three control-area. Buses 1 and 2 will be first control area, bus 3 is second control area and buses 4 and 5 are the third. Figure (11) shows all three control areas for under study system.

Under Study system has 3 major loads. They are variable loads and real data has been used for load variation. Also, the loads are dynamic loads to be more challenging and more similar to real grid. The details has been shown in table 2 and load changes curve illustrated in figure (12) This load data belongs to Semnan Province, Iran in 2010.

Proposed controller has been applied to all generation units, especially pv unit that is the source of disturbance in this system. The main control loop is based on a LFC system mentioned in figure (3).

Table 1-Parameters of generation units

Unit	Type	Bus no.	Nominal power (MW)
1	PV Gen.	1	40
2	Thermal	3	450
3	Thermal	4	450
4	Slack bus	5	---

Table 2-Parameters of loads

Load no.	Type of load	Bus no.	Nominal power (MW)
1	Variable	2	400
2	Constant	3	450
3	Variable	4	450

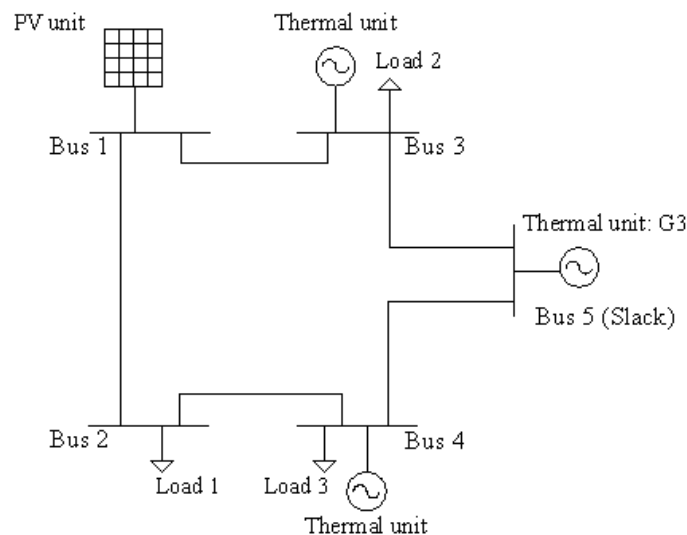


Figure (10) Model configuration of case study system

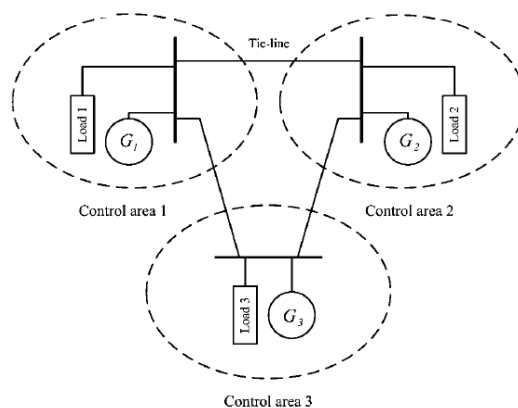


Figure (11) A system with 3 control areas used in case study

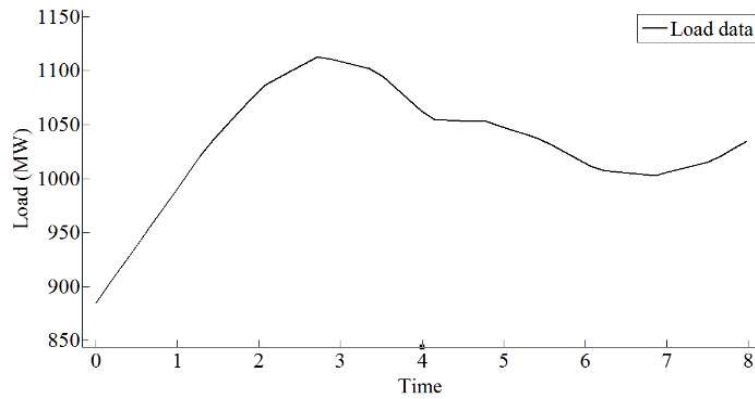


Figure (12) Real data for dynamic Loads used in case study

SIMULATION RESULTS

In this part, there is a comparison for grid frequency and other parameters between two conditions:

- Running with conventional controller (without proposed controller):**
 In the first condition, the system running with classic LFC controller. A simple and classic controller with ordinary PI control loop. In this condition, proposing controller is absent. This is ordinary working condition. In this situation, the frequency is almost stable around 50 Hz, but there is many variations due to PV-generation manner. This fluctuation makes typical generation units (thermal units) fluctuate and try to regulate the frequency and of course they cannot do it due to slow response of governor, turbine and classic controllers in comparison with dynamics of PVs.
- Running with the proposed controller:**
 In the second condition, proposed controller has applied to all generation units of the system, in other words controller applied to thermal units and PV-generation unit. To understand difference between two above conditions, it is helpful to take a look at figure (13) and figure (14); figure (13) shows a thermal unit with ordinary controller and figure (14) is the same unit with robust controller which proposed in this paper.

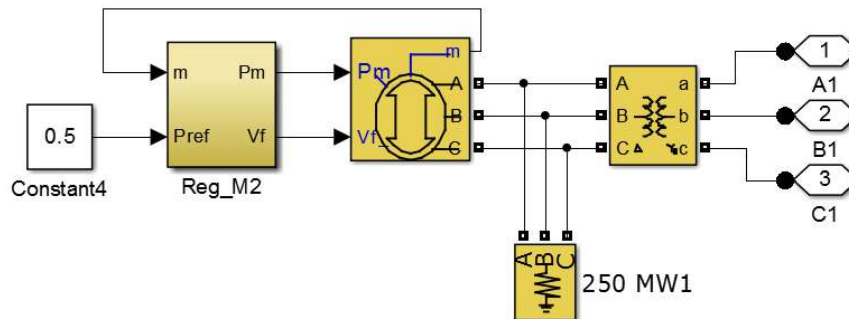


Figure (13) Thermal unit with ordinary (Classic) controller

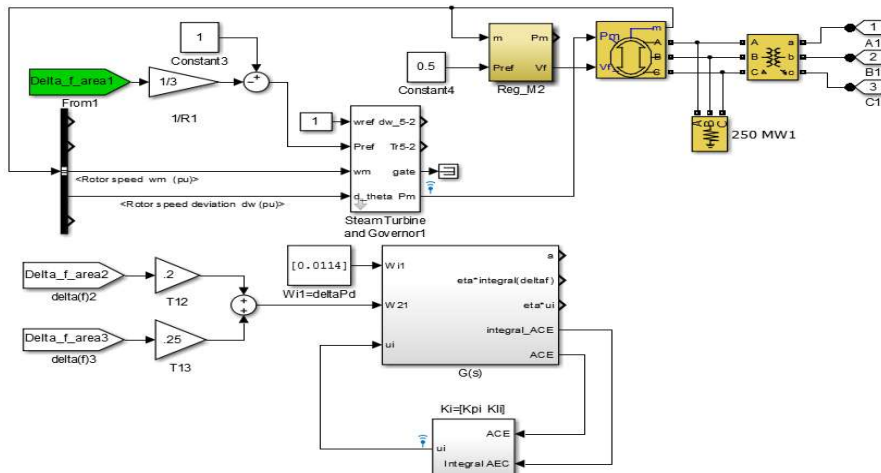


Figure (14) Thermal unit with robust controller (proposed controller)

Simulation result shows that proposed method improves system frequency response to disturbances. In understanding controller performance, it is useful to look at figure (15) and figure (16). Figure (15) belongs to U_i , that is the feedback loop for the control system. This feedback is observable in fig.2. Fig.15 shows that U_i feedback will be damped as time goes by, and finally it is fixed at certain value. This convergence happens while all loads are changing (figure (12)) and PV generation is fluctuating (figure (9)). Therefore, in this situation, convergence can be so hard and of course very important.

ACE of the first control area illustrated in figure (16). As mentioned before, ACE is a suitable linear combination of frequency and tie-line power changes, so it helps a lot to understand the performance of control system and the characteristics of power system. The value of ACE in ideal condition should be equal to zero, because in ideal condition frequency has been set to the reference value (here is 50 Hz) and each control area can regulate its own frequency, therefore no power will be transmitted between different control areas, via tie lines. In figure (16) the convergence trend of ACE1 can be seen, as time goes by, ACE is going to acquire zero value. This was main purposed of a nice and stable control system.

ACEs for all three control areas are shown in figure (17) and you can see that all of them going to be zero. The third control area is the point of common coupling (PCC), on the other words; grid meets the slack bus here. That is why ACE3 is more gentle with lower picks on its curve. Also, ACE1 has the biggest picks because the PV generation unit locates on bus 1.

Save the Best for Last, Figure (18) shows the most important result, which is the frequency of the system. This figure simply shows the difference between two conditions: power system conventional controller (with classic PI controller) and with novel controller (Proposed robust controller). Frequency variation in normal working condition (with classic controller) at some moments is 50.6 or 50.4 that is out of standard boundaries and it cannot be acceptable for usual working condition of a proper grid. The result shows that this robust controller makes the system respond faster and more effective on frequency smoothing. Figure (18) shows that the Pick point of frequency variations has been decreased to less than half. It is a great improvement in the power quality. Another Important point is that around seventh second of simulation, the system experiences a loss of load (around 5% of all loads), and it can be seen that the proposed controller handle this challenge appropriately.

There are some ripples on frequency, while using controller. That is because of the side effects belongs to proposed controller applied to PV unit. The reason is that controlling PV with applying mandatory pulses to the converter will cause this ripple.

The results show that robust control theory can effectively manage and regulate frequency variations and can help stability of the grid. This novel control theory is a fast controller and applicable in real-time mode unlike the controllers based on neural or genetic algorithms or fuzzy logic or adaptive controllers. Robust controller has simple structure. Also, when the number of control areas grows, this method still practical and useable.

In this paper, a new controller based on robust control theory introduced. Classic control in LFC and the reason it is not suitable for modern systems has been discussed. Robust control theory represented concisely. In addition, proposed controller Was introduced. Thereafter, a case study with simulation results presented.

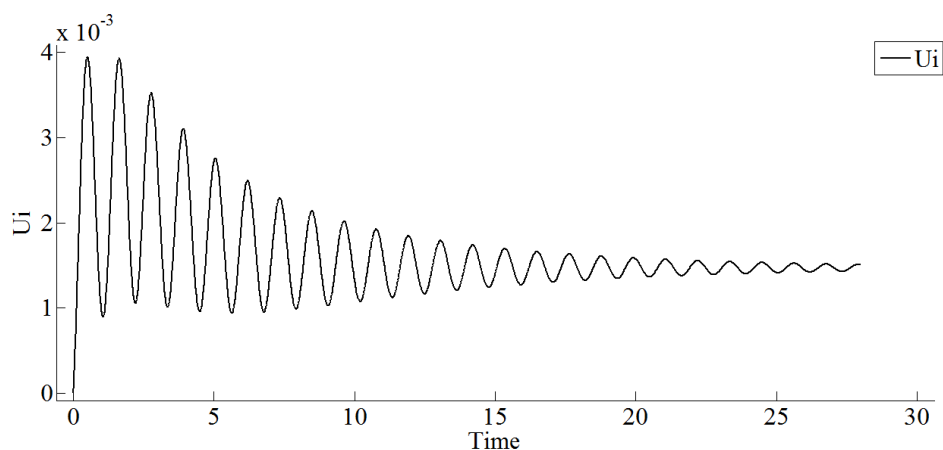


Figure (15) U_i (feedback value)

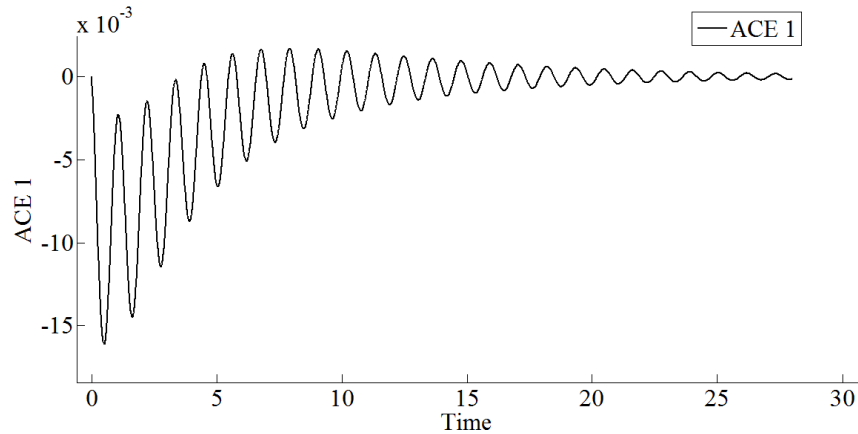


Figure (16) ACE for first control area, while using proposed controller

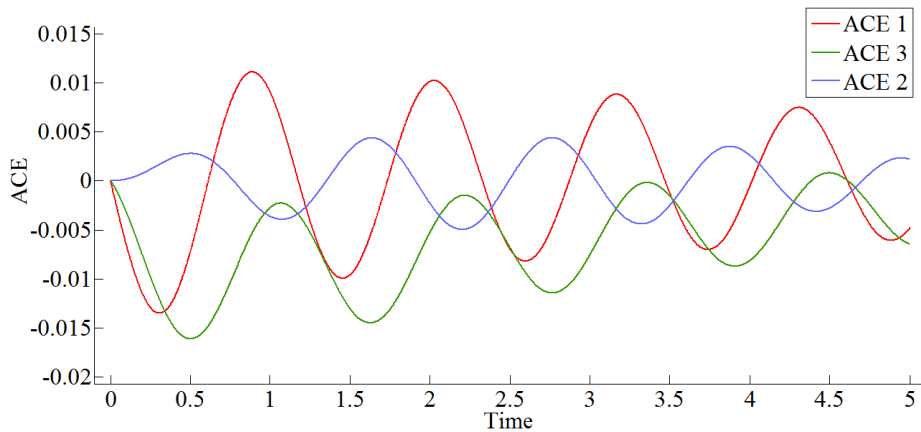


Figure (17) ACE for each of three control areas, while using proposed controller

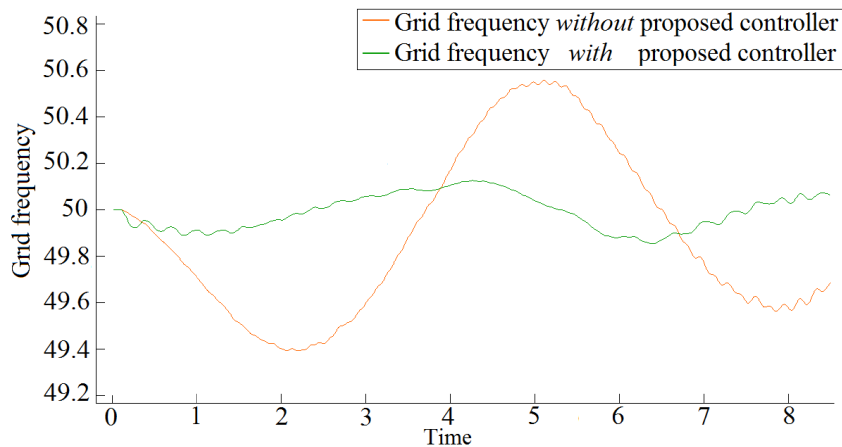


Figure (18) Comparison of grid frequency with classic and proposed robust controller

CONCLUSION

This controller will not help storage energy units as nice as it does generation units. As a record, this control system has been applied to a lithium-ion battery and although it works better than before, but the result was not as nice as expected. The reason is obvious; this controller based on LFC loop and it's specialized for generating units and may not be proper for storage energy systems.

In the case that frequency regulation services are met by conventional classic controllers, this controller is not damaging. Robust controller not only increase system operational efficiency but also make it possible for the system to accommodate renewable generation [18].

It is advised to Use a proper filter for converter belongs to PV unit. This action regulate frequency ripples and make it possible to have even better frequency in the grid.

Using this unit for wind generation has a very good conclusion. A study about the impact of the proposed controller on wind energy has been done and the results will be published soon.

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