Chapter 1

Introduction

1.1. Introduction and Literature Review

In this chapter of the thesis, a brief introduction about the multimachine and microgrid power network is explained with the problem statements. The essence of the controller design is discussed with a relevant literature survey. The motivations and foundation of the research carried out are reported in this chapter. Starting with the current scenario and background, this chapter includes the literature review, research gap description, motivation behind the proposed work, and thesis organization.

1.1.1. Overview of multimachine power networks.

Power system networks are required to be updated as per the current research to enhance the operational regime. Development in the power system areas suggests the incorporation of advanced control schemes, which can provide more resiliency and robustness to the power system operation. Power system operation in a multimachine is inherently stable, but the transient operation may be affected due to disturbances and parametric uncertainties. Unknown power system parameters may also affect the power system stability during transient perturbations. These parameters must be tuned accurately to compensate for the uncertainties in the power system networks or separate the nonlinearities due to these parameters in the control design. Therefore, a robust control algorithm is important to enhance the power system operating regime by providing additional damping [1]-[3] with the mismatched uncertainty interaction. Various significant contributions to excitation control is available in the literature, such as linear control, nonlinear feedback control, Linear matrix inequality (LMI) based control, sliding mode control, and backstepping control. The conventional excitation controller is mainly utilizing power system stabilizers (PSS) based on linearized models to extant the margin of stability [4], but the mismatched uncertainties are not focused on compensating. Even with the excellent suppression of low-frequency oscillation capabilities, these linear excitation controllers persist small range of operating point limitations [5]. Approaches based on LMI's also have small operating region limitations [6],[7]. Many other techniques are also available where the PSS method is combined with other controllers, for example, linear quadratic regulator (LQR), optimal control [8],[9], and robust control [10] for system stability enhancement. However, these techniques are established through linear approximation methods. Consequently, their performance degrades under large disturbances [11] as per their limited operating region. Also, no discussion of mismatched uncertainty compensation is present. These limitations under linear control algorithms and LMI's approaches are overcome by nonlinear excitation controller design that is independent of operating point constraints [12]-[14] and are employed in association with feedback linearization techniques.

The feedback linearization technique mainly has three divisions that are direct, exact, and partial feedback linearization, respectively [15]-[19]. The state transformation and nonlinear coordinate transformation approaches are respectively utilizing indirect and exact feedback linearization for the calculation of excitation control input. Both feedback linearization techniques have measurement issues in the selection of the synchronous generator's rotor angle as an output function. Therefore, these techniques require extra observers for rotor angle estimation, further enhancing power system complexity. The rotor angle measurement issue is resolved in [19] using the partial feedback linearization method, where speed deviation is taken as a direct, measurable output function. However, these controllers have high parametric sensitivity constraints resolved in adaptive nonlinear backstepping techniques [20]-[24]. Sliding mode control (SMC) techniques are used due to their excellent disturbance rejection capabilities as well as robustness against parametric sensitivity [25], [26].

In uncertain practical systems, the importance of mismatched uncertainties attenuation is realized through SMC control [27]. Also, LMI-based schemes, optimal control schemes, and adaptive schemes are applied for mismatched uncertainties attenuation, but these schemes have an assumption of bounded mismatched uncertainties using $H2$ norm. This is not a fair assumption as various practical systems may not essentially fulfill this condition of bounded $H2$ norm for mismatched disturbances. The synchronous generator is one of the examples of the combined mismatched uncertainties. Where bounded $H2$ norms of mismatch uncertainties cannot be introduced for mismatched uncertainty compensation [28]. However, due to the higher relative degree of power system dynamics, it is very difficult to design an adequate sliding surface. The controller can be designed in a generalized form, but the nonlinearity of the system is then compromised. The backstepping technique involves the recursive process of determining control law by designing virtual control through the system states. Then the error is formulated from the derivatives of virtual controls in each step of the backstepping control design process. This recursive process of designing the virtual control causes step errors in the virtual input that is required to eliminate using higher-order tuners [29]. Backstepping control is most appropriate for the power system dynamics of a higher relative degree, but the main complexity of this control procedure is to obtain a derivative of virtual control in each step; therefore, the implementation of these controllers is quite complex. This complexity has efficiently been solved using a command filter (CF) in the backstepping control algorithm [30] but it does not present any scheme for mismatched uncertainties. It decouples the iterations of virtual control derivatives while designing the backstepping control that is achieved from the integration of CF input. Therefore, the complexities in backstepping control implementation are substantially decreased due to the suppression of consecutive derivative operations [31].

Meanwhile, severe instability may propagate from one area to another due to the power system interconnection. Even it may result in an acute chain failure that leads to heavy economic losses [32]. Thus, the power system stability plays a vital role in safe operation. Also, the synchronous generator has nonlinear dynamical and complex interconnection in a power system network. Therefore, it is challenging to design suitable control for power system stability [33]. A New England 10 Machine 39 bus power system model is shown in Figure 1.1.1.

In advance, backstepping schemes power system unknown parameters such as transmission line parameters, damping coefficient of synchronous generators, infinite bus voltage, and direct-axis reactance are tuned through an adaptive law. But due to complex power system derivative terms and the recursive control design, the control input obtained is complex. It includes other power system variables which are parametric sensitive. This will enhance control computation and signal magnitude.

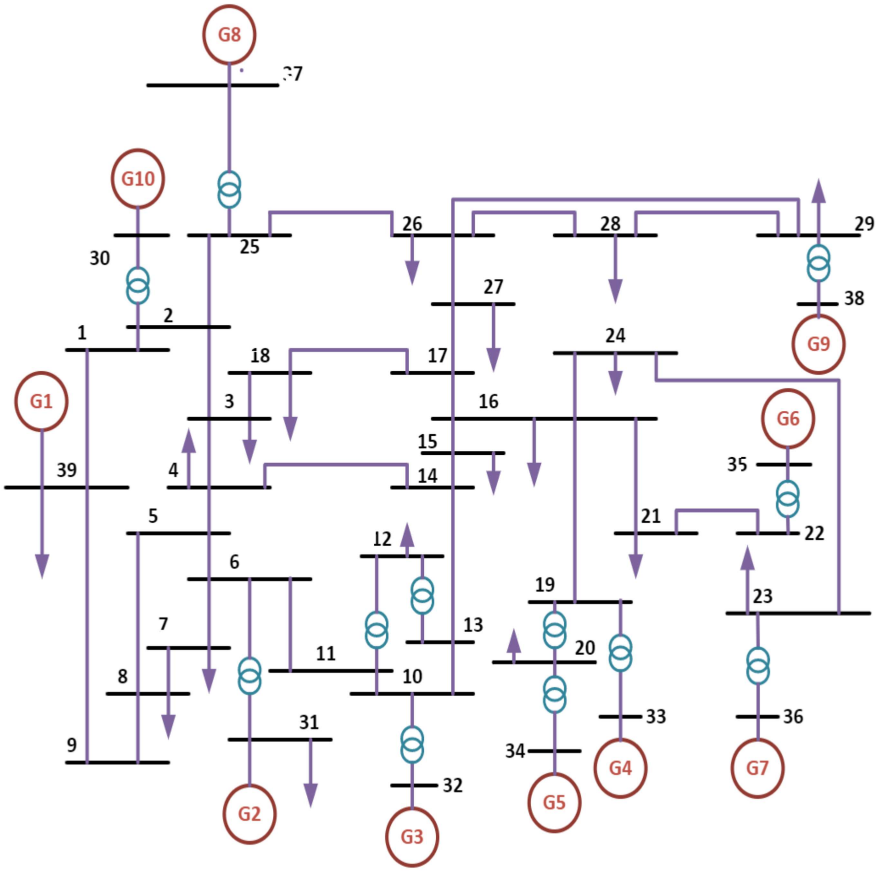

Figure 1.1.1. IEEE 10 Machine 39bus-based power system network.

The dynamic variation of power system model parameters may arise due to various uncertainties like changes in unknown parameters, external perturbations, noises in the measurement, severe faults, or load demand variations [34], [35]. Therefore, the control design must collectively report all these constraints.

1.1.2. Overview of microgrid power networks.

Like multimachine power system networks, microgrid power networks are also affected by system uncertainties and external disturbances. The microgrid is one of the effective solutions for renewable source integration and maintaining power balance under critical loads such as communication stations and data centers. In ac microgrid, voltage and frequency are determined by the utility grid in grid-connected mode or by activereactive power supply & demand in island mode. As in dc microgrid, the predominance of active power flow is solely responsible for dc-bus instability. The power fluctuation in microgrid is caused due to power flow unbalance between distributed generators and battery storage systems, Sudden changes in DC load, and the exchange of power between microgrid and the utility grid. For stability and improved power quality in microgrid, dc bus voltage can be regulated through dc-ac converter with bidirectional power flow capability. The conventional PI controller is then used to control the system dynamics. But the matched grid current, voltage, and power disturbance information are not considered. These control methods have limitations in accessing online microgrid asset information in real-time. It would be quite difficult to have the entire microgrid system information due to the scattered nature of DGs, loads, and battery storage systems. It is observed that many existing sliding surface designs are focused on matched uncertainty mitigation while the sliding motion of conventional SMC is only oblivious to matched uncertainties. In the event trigger schemes control signal will be updated as per violation of the triggering criteria, so it is a demand-based control technique. Triggering criteria are designed for the controller based on threshold inequalities in a way that the updated control is executed at the instant when the system trajectory crosses the defined threshold.

In addition to these issues in microgrid power networks, cyber threads are also a predominant issue that exists in the microgrid network. The cyber-physical structure can be represented by incorporating a communication network, power electronic devices, and software-intensive close-loop control. Because of the weak distribution grid, absence of generational inertia, and dynamic source-load profiles, the cyber threat becomes more noticeable in the inverter-based microgrid configurations. A cyber-physical microgrid structure comprises both cyber and physical layers, as illustrated in Figure 1.1.2. The physical layer signifies an interlink electric power system, whereas the cyber layer deals with the communication medium for the exchange of data between microgrid agents. These agents are interconnected by means of physical layer i.e., power lines, and ahead of physical nodes, cyber communication & information network connects the cyber components. Cyber safety in microgrids has dominant importance due to the occurrences of adverse, destructive, and undiminished cyber-attacks, particularly at the distribution grid.

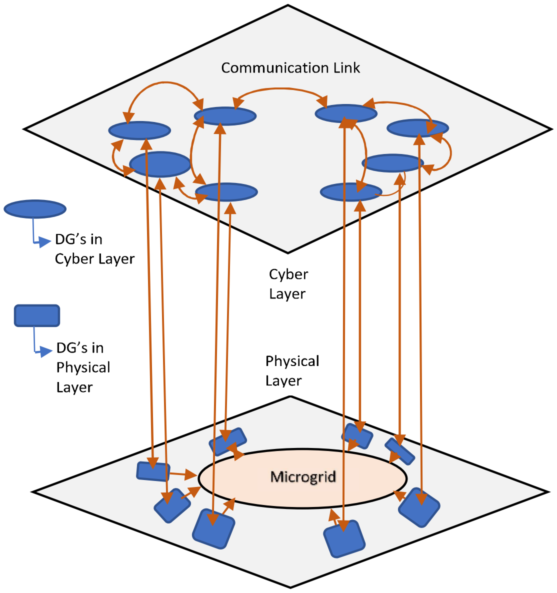

Figure 1.1.2. Multi DG-based microgrid cyber-physical structure.

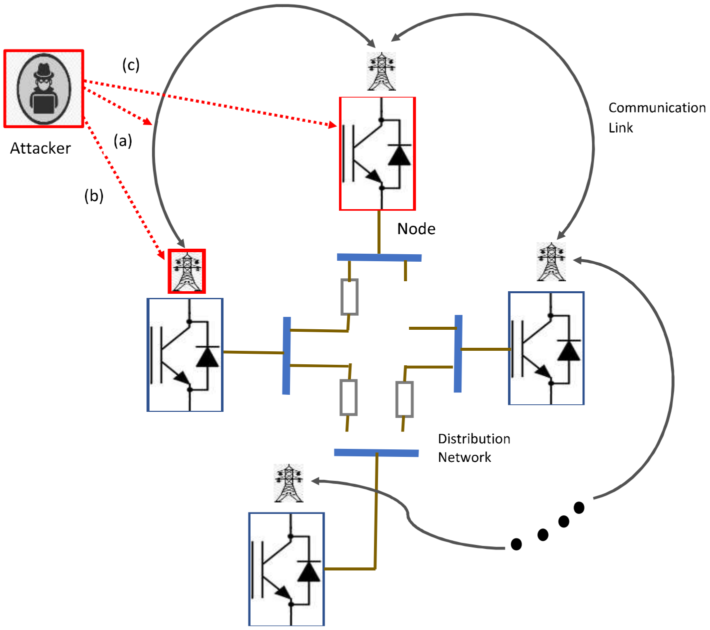

Figure 1.1.3. Different cyber threats in a microgrid. (a) In the communication channel (b) at the neighboring agent information for corresponding node (c) DGs state feedback signal.

In AC microgrids, the consensus control is primarily adopted to attain voltage and frequency regulation by information exchange between local neighboring agents. In a multiagent distributed AC microgrid, different attacks may deteriorate the system performance, as represented in Figure 1.1.3. In these categories, attackers can influence the signals from the leader node through the communication channel between nodes. The attacker may interrupt the neighboring node information and propagate false information to local nodes. Also, the attacker can inject an on-off signal to disrupt the local state-feedback signal. These cyber threat intrusions may be unbounded which can disrupt the synchronization of all agent's mechanisms.

1.2. The motivation and research gap.

1.2.1. For multimachine power networks.

In a multimachine power system, the difficulty in the stability regime arises due to complex interconnected networks and system-oriented nonlinearities. These nonlinearities cause instability in the system with the unknown power system parameters. Hence it is worthy of incorporating power system nonlinearity in the control loop. Various control schemes are thoroughly investigated, but the corresponding control design has a complex structure due to nonlinearity incorporation. Backstepping control design is the most exclusive and advanced control in the area of the multimachine system. But the lacunae in these controls are their complex control structure along with their multiple virtual control steps that enhances its vulnerability towards uncertainties. Along with these limitations, the indefinite control coefficient associated with the excitation control is required to be investigated in the power system network. With this motivation, proposed control schemes are explored in the thesis for multimachine power networks.

1.2.2. For microgrid power networks.

In the context of the control effort minimization in the microgrid operation the event-triggering scheme is analyzed in this part of the thesis. The literature associated with various control techniques is being thoroughly surveyed. The robust control action is required in the microgrid for strong disturbance rejection capability. In this part of the thesis an investigation robust control scheme like super twisting is carried out along with the event trigger phenomena. The gaps with the following points as mentioned below are emphasized and addressed in this chapter of the thesis.

1. Finite-time robust control action that suppresses the matched and unmatched

uncertainties simultaneously without any control signal chattering.

2. The event trigger-based control action can save significant control efforts during uncertain system fluctuations while ensuring system robustness under various disturbance conditions of the microgrid.

The other motivation in the microgrid network is to provide cyber resiliency. With this motivation a study of DOS attack in the autonomous ac microgrid is explored in the thesis. Where to avoid DOS impact, transmission times are designated to achieve closed-loop stability by satisfying suitable conditions at the time of communication under the DOS attack. The method is advantageous in the manner to achieve Input to state stability (ISS) subjected to disturbances under DOS attack through the general Lyapunov-based stability analysis during on-off timings of DOS attack.

1.3. Defined Control Objectives

The control objective of the thesis is categorized in two parts for integrated power system network. First the control objectives are defined for the high voltage power networks and then in the second category the control objectives are defined for the low voltage power networks. The control objectives in these categories are defined to enhance the power system performance in a wider regime.

Control objectives for high voltage power networks:

- To minimize the control complexity in the power system networks by separating the complex terms from the control design.
- To design adaptive laws for uncertain power system parameters which are sensitive to uncertainties in the system. These adaptive laws are to be designed to satisfy the overall system stability in the network.
- To enhance the robustness of the power system network and provide global stability to the network.
- To provide resiliency against actuation faults to improve the overall power system performance through the adequate scheme.
- To design a control scheme to subpress matched and mismatched uncertainties in the power networks through the observer-based schemes.

Control objectives for low voltage power networks:

- To improve the control efforts in the low voltage power system networks during perturbation by the application of event trigger algorithms.
- To design observer-based control scheme for the compensation of matched and mismatched uncertainties.
- To enhance the robustness against the system disturbances by using robust control schemes.
- To provide resiliency against the cyber threat and actuation faults in the low voltage power networks.

1.4. Thesis Organization

The thesis has been segregated into seven chapters, starting with the table of content, List of Figures, List of Tables, and List of abbreviations & symbols, the preface of the thesis is arranged. After the preface, the first chapter of the thesis as the Introduction is to be arranged, in which literature review, motivation and research gap is discussed. The other subsequent chapters are arranged as:

- ➢ Chapter 2: Resilient Optimal Gain Control and Continuous Twisting Observer for Enhanced Power System Performance Under Uncertainties.
- ➢ Chapter 3: Entirely Coupled Recurrent Neural Network-Based Backstepping Control for Global Stability of Power System Networks.
- ➢ Chapter 4: Global Adaptive Asymptotic Performance with Indefinite Control Coefficient and Adjustable Parameters in Power System.
- ➢ Chapter 5: Event Trigger Super Twisting Sliding Mode Control for Microgrid with Matched/Unmatched Disturbance Observer.
- ➢ Chapter 6: Denial-of-Service Attack Resilient Control for Autonomous AC microgrid
- ➢ The conclusion and future work are provided in the last chapter of the thesis.

After the conclusion part, all publications corresponding to the thesis work are provided next and at the end of the thesis, all corresponding references are placed sequentially.