Synopsis

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Rapid urbanization, industrial growth, and ever-increasing population have tremendously resulted in the increased demand for electricity. Any nations growth can always be linked with the per capita consumption of electricity [1]. This increased demand for electricity can only be commensurated by enhancing the generation capabilities up to some feasible extent, beyond which it has its economic and environmental repercussions. Conventionally, the generation of electricity has extensively depended on fossil-based resources (e.g., Coal) and sustainable energy sources (e.g., Nuclear). The rapid growth of the energy sector has started depleting non-renewable and fossil-based energy sources and has caused considerable damage to the environment due to greenhouse gas emissions. Stringent environmental treaties (viz. Kyoto protocol) have enforced the signatory nations to break on to the carbon emission to prevent the damage to the environment beyond an irrecoverable extent or a point of no return.

These factors have opened up new avenues in the field of energy generation and conservation. There has been evolved a new field called Demand Side Management (DSM) [2], which has emphasized efficiently managing and manipulating the electricity demand rather than enhancing the generation capabilities of electricity to bridge the gap between demand and supply. A few of the strategies of DSM, along with its posing limitations, can be listed as:

- Real-time pricing - [3][4][5] Greater the demand of electricity greater is its price and vice-a-versa. This mechanism is not capable enough to match the load demand, in real-time.
- Peak demand shaving by the use of:
  - Energy storage [6] - Batteries happen to be the most reliable option of DSM, but have limited life, high initial cost [7] and disposal of the same poses serious environmental issues. It can be made viable by reducing its size and hence its cost.
  - Direct load control or On-Off control, also referred to as smart on-off control of the load based on its criticality [8][9].
  - Scheduling of delay-tolerant load [10][11][12] - Clipping the peak and by shifting the same to some other point of time called valley filling.

Implementation of these methods causes discomfort to the customer, and at the same time, it needs high-speed communication infrastructure, which may result in the compromised privacy of the customers, by intruders and hackers.

More significant environmental concern has opened up the new era of tapping and harnessing the renewable energy sources (RES) viz., wind and solar, for the generation of electricity through distributed generation, without incurring any wheeling cost that too without adversely impacting the environment. This integration of RES into the distribution grid has a detrimental impact on the electrical system, as it causes oscillations and disturbances which have been hampering the steady-state stability of the power system [13], due to its intermittent and unpredictable nature and, in a way pollutes the electrical power. Furthermore, the unpredictability of RES creates issues in the day ahead forecasting, scheduling, and bidding of the power, in the new regime of the restructured/unbundled power system [14].

There has to be a system that could avert the ill effects of voltage fluctuation, caused due to the inclusion of RES in the distribution grid, and further, this could affirm the expected and satisfactory operation of electrical equipment connected with it. Few mechanisms such as Flexible AC Transmission System (FACTS) devices have long been present to restrict the destabilizing effects of power oscillations to a minimal extent and have been given a place in the restructured power system ancillary services. FACTS devices demand huge investments and can only be proved feasible with the application in the transmission system. A somewhat more petite version of FACTS has been thought of as being inculcated in the distribution system, known as distribution FACTS (D-FACTS), to reduce the destabilizing impact of RES.

The Indian government, through state administration, is promoting and encouraging the installation of the solar rooftop system at the customers end, by subsidizing it and at the same time also doing a purchase agreement for surplus electricity generated therein [15]. Purchase agreements of this nature have provided an impetus to the generation of electricity through solar energy. Bulk inclusion of the solar rooftop system is going to create voltage disturbances and hence will need a solution form within, i.e., at the customers end.

Electric Spring (ES) [16] happens to be one of the plausible answers to the problem of voltage oscillations inflicted by RES, with a reduced or no extra power demanded by it. It has been named so because it mimics its mechanical counterparts action, which absorbs the thrust or impact by providing the voltage regulation and minimizing the oscillations caused by the distributed generators intermittency. It is a custom power device [17], (a voltage source converter) connected in series with part of the total load called a non-critical load. Together, this combination forms a smart load and serves the other part called a critical load, and the distribution grid is catering to this whole system. Here it is worthwhile to note that the lord of the customers installation can always be bifurcated, based on the nature of its criticality. The dissipative or delay-tolerant load (e.g., HVAC-heating, ventilating, and cooling type loads), which can have a share of around 70% of the total load of a customers installation [18], can survive the voltage fluctuation, acts as a non-critical load, and the other part which is less tolerant to voltage variation has been considered as critical load.

Ever since the inception of the ES [19], like the other devices, it has also been evolved by accommodating the various changes in its configuration. The evolution of ES can be presented in the form of different generations as, (i) 1^{st} generation ES – whose DC bus possesses an aptly sized capacitor, to handle reactive power only, (ii) 2^{nd} generation ES – battery is connected on the DC bus, which can handle active as well as reactive power) Furthermore, (iii) 3^{rd} generation ES –whose DC bus is connected to the grid through a converter.

1^{st} and 2^{nd} generation of ES work better to prevent under-voltage than to suppress over-voltage; further, its voltage regulating ability dramatically depends on the characteristics of the load. 3^{rd} gen. ES with a back-to-back converter configuration works better to overcome the limitations of earlier generations of ES by extending the operational flexibility [20], but is lacking the reliability for the reason that it is incorporated with an additional converter to be controlled, to tackle with the bidirectional exchange of power and to restrict the proliferation of harmonics to the grid as prescribed by the standards viz., IEEE-519. ES emanates voltage (v_{es}) so as to bridge the gap between the difference of voltage being supported by the non-critical load (v_{nc}), and that demanded by the critical load (v_c), i.e.,

$$v_c = v_{nc} + v_{es} \tag{1}$$

The Control system of ES is the key to the successful generation of the desired constant voltage (v_c), across the critical load, by injecting v_{es} through ES. Numerous methods of generating v_{es} have nicely been presented and explained through phasers in [21]. Various non-optimal and traditional controllers for controlling the ES has been demonstrated in the published literature [22][23][24][25].

This work has been focused on the application of Second-Generation-ES as an efficient mechanism of low-cost real-time Demand-Side management, with a focus on the various control aspects of the same. A mathematical model of ES, using the state-space method with the system being considered a multivariable one, has been used to design various controllers being verified in this work. The considered model possesses numerous uncertainties viz., viz., variation in voltage of DC bus, Load change, change in grid voltage, and change in cable length causing a change in the cables impedance. The designed controller has to have enough robustness to combat these variations and uncertainties. Further, parametric variations made the systems model a polytopic [26] one, which further complicates the controller design.

This work has been started with the most basic and widely used variant of the controller, i.e., a PI controller. The same has further been modified by incorporating cascaded control by implementing an inner current control and outer voltage control loop through PI controllers to put a check on the current handling capabilities of an ES.

Another non-optimal variant of the PID controller, i.e., a lead-leg compensator [27], an upgraded variant of PI controller, has also been formulated to carry out the control of ES. Results of these two control strategies, i.e., one degree of freedom and a two degree of freedom [27] controller, have been compared with that of a Lead-Lag controller. Limitations associated with these controllers' non-robust performance, amidst the parametric and voltage excursions, have motivated to try and test the modern control techniques for the control of the ES.

A robust Linear Quadratic Regulator (LQR) has been tried for the control of ES. Steady-state error in the output has provided an impetus to add an integrator in the existing structure of LQR (LQI Control) [28]. An integrator has been further added to the control loop to reduce the steady-state error to zero. There could be exist numerous control gains, that bring in the stable control to ES [29], using non-optimal control effort. This has been a motivating factor to go for the development of an optimal LQI controller, and the same has been proposed for the control of ES, in this work.

Numerous optimization techniques have been presented in the available literature, and a judicious selection of the optimization technique happens to be a task. The model of ES's system can be at the most built up to the 5^{th} order. Consideration of any of the heuristic or meta-heuristic methods of optimization seems to be non-essential for the reason that it requires much time in the training of the network, and further, optimization of such a small system can easily be obtained through any of the numerical methods of optimization using either Linear Programming (LP) or Semidefinite Programming (SDP) approach. It has been decided to go with Linear Matrix Inequalities [26][30][31] (LMIs), an approach of SDP, for the reasons, that it is simple to implement in Matlab (using *Robust Control Toolbox*) and yet it is an efficient way of optimization for both the monotopic as well as polytopic models.

A phase-Locked-Loop (PLL) happens to an integral part of a power electronics converters control, as phasor information along with the magnitude to be compensated is inevitably needed. The design of PLL for a system operating with power frequencies has to be tackled with a different strategy than a basic PLL structure (being used with the communication systems), for which it was invented. Two different PLL design methodologies, one using a Lead-Lag compensated approach [32] and another with an enhanced one, i.e., E-PLL [33], have been carried out and tried in the control of ES.

Further, it has been tried to justify the role of an ES as a device commensurating and fulfilling the requirements of demand-side management (DSM)[2] on a real-time basis, by accomplishing the peak power shaving, that too without shifting the power demanded by the Load at some other point of time (valley filling), on the time axis.

The work in this thesis has been organized as follows:

Chapter-1 presents the basic idea of Demand Side Management (DSM), along with its tools and techniques. This chapter also presents the significance and scope of this work.

Chapter-2 represents the state-of-art, and discusses about the factors that have lead to the emergence and evolution of Electric Spring. Further, it gives an idea about the design and development of a basic system (test bench) mimicking the distribution system, loads, and ES and associated aspects that could be commonly used to verify the various controllers, to be presented in the upcoming chapters. A mathematical state-space model of the system has also been derived and presented here.

Chapter-3 has been dedicated to the design, implementation, and testing of different Phase-Locked-Loop structures, to be used in conjunction with the control of ES, for the creation of phase angle reference.

Chapter-4 presents a PI controlled ES. There also has been presented the cascaded control mechanism, wherein the inner loop has been dedicated to the current control, and the outer loop has been incorporated with voltage control, so as to limit the current in the case of larger disturbances and faults, along with the voltage regulating abilities of ES.

In **Chapter-5**, a Lead-Lag controller has been designed and developed to verify its efficacy in controlling the ES.

In **Chapter-6**, an optimal Linear Quadratic Controller using an integrator has been presented for the control of ES. The said controller has been optimized through Linear Matrix Inequality, a numerical convex optimization approach.

In **Chapter-7**, a detailed comparative analysis of the results obtained in Ch-4, Ch-5, and Ch-6 has been recapitulated.

Chapter-8 summarizes the main findings and their importance as well as the contribution of the thesis. Lastly, this chapter also provides a few suggestions for the future expansion of this work.

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