Chapter 1

Introduction

1.1 General

The quantum of electrical energy consumed by a nation is an indicator of its progress in socio-economic terms. Conventionally, electrical energy generation has been heavily dependent on fossil-based sources, viz. coal and diesel, which happens to be the prime source of greenhouse gasses and causing pollution of the environment. Greater awareness and concern about the environment have posed many restrictions on the emission of greenhouse gases, proliferated by conventional generating sources, through stringent standards and treaties, on which the world leaders have agreed upon. Stringent environmental treaties like Kyoto protocol have put some research areas of electrical engineering (viz. FACTS devices (Flexible AC Transmission System), custom power devices (CPDs), demand-side management (DSM), smart grid, etc.), on a fast lane. There is a paradigm shift towards the greater inclusion of non-polluting and green renewable energy sources (RES) in the grid, along with the curtailment of polluting and emitting conventional fossil-based sources of electricity generation. To curb the menace of carbon emission, India has set an ambitious target of harnessing 60 GW of power through wind and 100 GW by solar, by the year 2022 and is planning to raise the share of RES by 60% of the total electricity generation, by the year 2030 [1][2]. Bulk inclusion of RES leads to loss of stability of the electric grid due to its intermittency. The unpredictability of the RES causes market-related issues in the regime of the restructured power system. Forgoing discussion reveals that electricity demand increases day by day, which can only be catered through fossil-based bulk generating sources, polluting the environment. On the other hand, the cleaner option of the same, i.e., RES, are causing pollution [3] of the electrical system itself.

Through the state government energy policies [4], India's government has been promoting the inclusion of solar roof-top-based grid-connected generation and integration of the same in the distribution system, which is going to version the stability issues in the secondary distribution side of the grid.

Many research publications have been available to address the issue of voltage regulation at the transmission level and at the primary distribution level, in the form of FACTS devices and D-FACTS devices, respectively. Not many efforts have been made to address the issue of poor stability at the secondary distribution level, which will face poorly regulated voltage due to bulk inclusion and stochastic nature of grid-tied solar generation being present at the individual consumer's roof-top.

The gap between the demand and supply of the electrical energy, and the bulk inclusion of RES, leads to hampered and compromized stability [3] of the grid. The cause of instability is due to the intermittent and unpredictable (stochastic) nature of RES, and this can only be addressed by resorting to some means of load management rather than generation management. Area of Demand-side management (DSM) [5] has emerged as a method of reliably catering to the overall demand of electricity by managing the load rather than increasing the generation.

Electric spring (ES) falls into the domain of custom power devices because it is of small to moderate rating and could directly be commissioned at the consumer's premises for voltage regulation. The ramification of instability in the distribution system due to oscillations created by intermittency and emerged due to the bulk inclusion of RES in grid-tied solar roof-top systems could be readily available through ES having reduced energy demand as that compared to UPS. The idea of ES [6] has been initially derived from its mechanical counterpart (mechanical springs), working on the principle of Hook's low, being used in the mechanical system to absorb the shocks and provide the support in the case of mechanical thrust. ES can address voltage regulation that has emerged due to the intermittency of RES's in the distribution system. Its configuration and control make it unique in terms of its voltage regulating capabilities (additionally, it can also be used for frequency control in micro-grids). By connecting several dispersed electric springs throughout the distribution system at different points in an electrical network, oscillations developed due to intermittency can be damped out, like a mattress being supported by an array of mechanical springs.

Categorizing the load into critical and non-critical ones has nicely been utilized in the concept of ES to optimize its rating and associated battery storage. A load of any installation can be bifurcated into:

- **Critical load (C)**: This is the load that is very sensitive to voltage fluctuations. It can not survive even a small variation in voltage if it jumps slightly beyond the prescribed limits. Data centers, Surgical types of hospital equipment, types of equipment operating with and being controlled by micro-controllers, etc., are amongst the few contenders that could be accommodated in the category of critical loads.

- **Non-critical load (NC)**: This category of the load is constituted by dissipative loads, such as heating, ventilating air-conditioning (HVAC), and lighting loads. It can easily survive the voltage fluctuations and is occupying around 68% [7] of the total load.

The critical load is connected across the series combination of non-critical load and ES, which happens to be a series-connected current-controlled voltage source converter (VSC) [8][9], collectively being supplied by the distribution system. The duo (series combination ES and NC load) is acting as a smart load to maintain the voltage to a preset value, across the critical load, in the event of intermittency of the grid voltage. The significance of the controller controlling the switching of the ES is paramount, as it decides the magnitude and phase of the voltage to be injected.

1.2 State-of-the-Art

The advent of Smart grid [10] has brought about a paradigm shift towards demand management [11][12] rather than generation management [13], which is known to have been prevailing in the conventional power grid ever since its inception, as a control and management paradigm.

Demand Side Management (DSM) is a concept inculcated with the set of procedures adopted by the grid operators so as to utilize the electrical energy optimally when it is available at low cost and to shun the excess demand of the same when it is not available as per the demand, and hence reducing the cost of electrical energy from the perspective of grid operators, and consumers [14].

These mechanisms of DSM could be elaborated as Price Responsive Demand and Demand Response (DR) Programs. The Demand Response Programs can be defined as the customer's ability to alter the demand in response to forecasted one by curtailing the same in the event of deficiency in forecasted demand. It could also be linked with the tariff, in the form of Price-responsive demand, by applying changes in their electric load profile in response to energy market price through the implementation of real-time pricing. In short, it is a mechanism of improving the efficacy of electricity markets by encouraging the consumer to take advantage of lower tariffs (during off-peak hours) by increasing the utilization of electrical energy and discouraging it when it is high (during peak hours). This is being achieved through peak shaving and valley filling mechanism in the load profile. In this way, the peak demand and hence the need for additional generation capabilities in the form of spinning reserve and transmission infrastructures could significantly be reduced [15][16].

The rapid pace of growth in the Internet and Communication Technology (ICT) has made more and more electrical loads compliant with control through ICT. This new paradigm of DR is called demand dispatch, and this helps in bridging the gap between the generation and demand of electricity by efficiently utilizing it. Demand dispatch will be an essential enabling technology, which will allow higher levels of penetration of intermittent and unpredictable RES in the electric grid.

1.2.1 Limitation of Demand Side Management

Few of the mechanisms of DSM have been listed here, along with its posing limitations:

- Real-time pricing [17][18][[19] – Higher the demand higher the price and vice versa. This mechanism cannot match the load demand through the appropriate quantum of electrical power generation in real-time.

- Peak demand management by the use of:

    1. Energy storage [20] – Batteries happen to be the most reliable option of DSM, but with a few adversities like limited life, high cost of the system [21] and

disposal of the same poses serious environmental issues. It is preferable to reduce its size and hence its cost.

2. Direct load control or On-Off control [5][22][23] – As per the norms of the prevailing contract conditions with the consumer, the distribution company can switch the ICT-enabled load through a communication network, and this may cause discomfort and debilitated and compromised convenience of the end user.

3. Scheduling of delay-tolerant load [24][25][26]– This works on the assumption that load is having ample elasticity and the operation of the same can be shifted to the valley region of the load curve to chamfer or clip the peak of the curve. The same can not be made possible with the non-elastic loads, and hence DSM could not be made feasible to a great extent by employing this mechanism.

4. Using the energy-efficient devices–Use of energy-efficient motors in the loads like refrigerators, AC, pumps, fans and switching to energy efficient luminaries viz., CFLs, LED etc., could reduce the load to a great extent, but needs huge capital cost of replacing the existing infrastructure.

Implementation of methods mentioned above in 2 and 3; causes discomfort to the end-user as it does not match the demand of the load in real-time, for the reason that it exploits the use of the elasticity of a typical load. An Elastic load could tolerate the delay in its usage and vice versa. The techniques referred to as on-off control uses some sort of communication network that comes with a bunch of issues like an extra cost, latency in the signal traversal due to limited bandwidth of the network, and the possibility of hacking and intrusion into the life of consumers.

1.2.2 Compliance through Electrical Spring

The best option of DSM that could be marked out from the prevailing discussion is the use of storage mechanism through the use of batteries, for the reason that it could employ DSM in the real-time without looking at the elasticity of a given load, and could be implemented through the use of uninterruptable power supplies (UPS). Load does not require any delay or shift in this case. The limitations associated with the batteries' excessive cost could be partially mitigated by reducing the storage system's size. Storage reduction can easily be implemented using ES [27], compared to what is required in UPS. Thus, ES can function as a mechanism of furnishing DSM on a real-time basis, without falling into the intrigue intricate of shifting or relocating the loads into the valley region of the forecasted load curves, that too with cost optimization and without falling into the vicious trap of hacking and intrusion in the personal life through the use of ICT.

Ever since the inception of ES [6] by S. Y. Hui et al., it has been evolved through the generations. The DC bus of 1^{st} generation ES [28] is incorporated with an appropriately sized capacitor. The prime reason for adopting this structure lies in its operational simplicity and non-mandatory knowledge of grid voltage and circuit parameters. The obviated shortcomings are (i) weak decoupling (ii), non-operational non-critical load in the event of failure of ES, and (iii) only supporting the reactive power.

Enhancement and flexibility in the control of 2^{st} generation ES, due to the presence of an active storage element (in the form of battery storage acting as a DC-bus), offers the control of active as well as reactive power with an additional degree of freedom and putting it to a level higher than that of 1^{st} generation ES. This ES with its steady-state analysis has nicely been presented in [29] and further, it was established in [27], that there is a reduction in energy storage requirement (of the DC-bus). Dynamic modeling of the same has been provided [30].

The third version of ES (3^{rd} generation of ES) [31], comprising of back-to-back (AC-DC-AC) connected bi-directional converter, having one of them (AC-DC converter) connected between the grid and the DC-bus of ES and responsible for the drawal of power needed for its operation, and the second one (DC-AC converter) connected between DC-bus and load is acting as ES. This has also been implemented with the micro-grid application for extending its operational limits through coordinated battery management for reducing voltage and frequency fluctuations, in [32].

Being a custom power device, configuration and operation of ES, is resembling with that of many FACTS devices and a nice comparison of ES with STATCOM [33], SSSC and DVR, has been presented in [34] and ES complying with the paradigm of DSM has also been established here. Multiple ES, being dispersed throughout the distribution system at the multiple consumers' location, functions even better in the coordinated manner, using the concept of Droop control (without using ICT) of ES has been presented in [35] by establishing the similarity of the concept of droop controlled ES with that of a spring supported mattress. So far the presented ES has been functioning with the configuration of 1-ϕ half-bridge [29] or full-bridge converter [27][35][36]. Application of ES in full-bridge converter configuration has been proven more advantageous than the half-bridge, which is simpler to implement.

A 3-ϕ variant of ES has been proposed for reducing power imbalance [37] and nullifying negative-and zero-sequence currents in an unbalanced 3-ϕ system in [38].

ES has also been proposed to be operating with the micro-grid for voltage and frequency control [39]. It has been implemented in the grid-tied mode [32][40] and reduction of power loss in islanded AC micro-grids using dispersed ES using predictive control [41] and few more papers could also be cited on the same topic [30] [41][42]. Different operational modes of ES for the application voltage and frequency control of micro-grid have nicely been elaborate in a lucid manner in [39], with the help of phasors. Practical evaluation of droop and consensus control of distributed electric springs for both voltage and frequency control for micro-grids has been tried in [40]. The concept of ES has also been extended to serve the DC micro-grids in [43]. Distributed cooperative control and stability analysis of ES for DC micro-grid has been verified in [44]. In [45], ES for improvement of voltage quality has been proposed.

Almost each of the literature published on the topic of ES has been accommodated with uniqueness in terms of its control aspect. The controllers ranging from the most primitive, conventional one, i.e., PI, to the advanced one using heuristic control, could be cited from the available literature. Optimal control of ES, using Jaya Algorithm [46] and optimal time domain-based objective function for the reduction of time-weighted voltage deviations [28], could also be found in the literature. Newly formulated control algorithms using the conventional controllers (viz, PI and PR controllers) could also be found in the literature. Few of the examples could be listed as:

- Novel δ control, using PR- controller [47]
- Simple decoupled control through d-q frame, using PI controllers[48][49]
- Radial-Chordal Decomposition Control, using PI controller [48]
- Adaptive PI control [50]
- Repetitive Control, using quasi-PR controller [51]
- Modified decoupled control, using a PI controller in d-q frame [52]

1.2.2.1 Classification of ES

An ES can be classified on the following basis:

1. Based on the type of the converter being used:
   (a) Voltage Source converter
   (b) Current Source converter [53]
2. Based on the type of DC bus being used:
   (a) 1^{st} generation ES, holding a capacitor at the DC bus, and can produce the support of reactive power only [6].
   (b) 2^{nd} generation ES, holding a battery as a storage element at the DC bus, and can support active as well as reactive power [27][30].
   (c) 3^{rd} generation ES, possessing a bidirectional (AC-DC-AC) converter, drawing power from the grid and supplying to the ES, and can handle active and reactive power as well [31].
3. Based on the type of the source of the grid with which it is being used:
   (a) AC ES.
   (b) DC ES [44][45].
4. Based on the stiffness of the grid with which it is being used:
   (a) Stiff Grid–used with the main grid, having moderate power application.
   (b) Weak Grid–used with the micro-grid applications, having low to moderate power application:
      i. Islanded mode of micro-grid – used for the control of voltage and frequency [30] [41][42].
      ii. Grid tied mode – used for voltage control [32][39][40] .
5. Based on the:
   (a) Solo mode of operation.

   (b) Multiple ES's working in tendon – working cohesively in the droop-control mode [32][35][40].

6. Based on the type of control:
   (a) Employing Classical control techniques:
      i. PI controlled [54][30][34][35][39].
      ii. optimal time domain-based PI controlled[28]
      iii. PR controlled [36][51][55]
      iv. Lead-Lag controlled [56]
      v. Cascaded PI controlled.
   (b) Employing Modern control techniques:
      i. LQI control.
      ii. H-infinity control.
      iii. Sliding mode control.
      iv. Employing Heuristic or Meta-heuristic control[46]S.
      v. Predictive control [41]
7. Based on the application with number of phases:
   (a) 1-ϕ application [29] [34][35].
   (b) 3-ϕ application [38].
8. Based on the type of PWM technique used in the converter:
   (a) SPWM control [29][34][37].
   (b) sigma delta modulation.
   (c) SVPWM control.
9. Based on the frame of reference, used for the execution of the control:
   (a) Stationary reference frame – using $\alpha - \beta$ frame, P-Q frame.
      i. 1-ϕ application.
      ii. 3-ϕ application.

(b) Synchronous reference frame – d-q frame.

i. 1-ϕ application [48][49][52].

ii. 3-ϕ application .

(c) Natural frame of reference.

10. depending on the type of configuration of the converter:

(a) Half bridge configuration [54][29][30][34].

(b) Full bridge configuration [27][35][36].

1.3 Motivation

Prevalent research has been briefed in the form of state-of-art, and study of the same have revealed few missing links or research gaps, and the same could be presented as:

- The published literature has presented the context of a developed nation, where variation in the voltage is not violating the limits of $\pm 10\%$. Unfortunately, the same is not the case with developing nations like India, where voltage regulation is commonly hitting and many a times even violating the limits of $\pm 20\%$.

- Modeled system of ES has been presented as a single-input-single-output (SISO) system in the published literature, whereas in actual it is a MISO system, having grid voltage acting as a disturbance input.

- Parametric variations associated with the system of ES have not been included in the study of ES. Consideration of parametric variations (in $V_{dc}, v_g, Z_g, Z_c,$ and Z_{nc}) requires a robust controller design having quiet larger bandwidth. Controller possessing large bandwidth comes with a sluggish response. Hence, optimization of the control structure is a must, which comes under the domain of modern control techniques. Still, the same has not been addressed appropriately and justifiably.

- In many of the papers, the controller has been designed with an assumption of fixed load condition, which has never been the case with the actual system.

- PLL is a critical component in operation and hence its study of grid-tied inverters. Requirements of a PLL structure being used with the power frequency signals are altogether different from a PLL used with the communication signal. PLL and its robustness have not been presented in any of the available literature on ES in greater depth.

- In many papers, the non-critical load has been considered a variable entity, keeping the critical load fixed and constant. In actuality, critical load happens to be a variable entity, and the function of non-critical load should be supportive to the ES so as to constitute a smart load.

- Grid impedance is playing a crucial role in the controller's performance and hence ES, which happens to be depending on the many things (viz., length of the conductor, type of the conductor etc.) and hence is a variable entity, which has been considered fixed in the available literature.

- Optimization has been addressed through the use of heuristic and meta-heuristic methods, which happens to be an ideal contender for more extensive systems of higher order. The system of ES never exceeds the 5^{th} order, for which numerical optimization should have been considered to achieve much higher accuracy and efficacy in the controller's performance.

- Few fundamental yet proven controllers viz., Cascaded PI control, Lead-Lag control, LQR control have not been tried and tested for the application of the control of ES.

A thorough review of the available literature has revealed a few of its limiting factors. The limitations have motivated us to decide the line of action for the execution of this research, and the same has been ticked out as:

- To design an experimental testbed implemented with the adversaries commonly prevalent in the Indian distribution grid, which is hampering the satisfactory and conducive voltage conditions, and they are:

  - Variation in the voltage available to the load due to the variation in the grid voltage (±20%) being witnessed due to the impact of intermittency of distributed generators (DGs) present in the form of RES.

  - Variable impedance of the grid, due to the variable length of point of coupling of the load, causing the variable drop in the voltage.

- To develop the control structure of the ES, accommodating the adversaries mentioned earlier in the testbed, so that the designed controller's robustness can be verified.

- Controller design needs a mathematical model of the system and not the converter, which happens to be a Multi-Input-Single-Output (MISO) system, and hence the system's state space model is to be carried out in this manner so as to design an appropriate controller for the system of ES.

- Performance of the ES is to be tested using the classical control techniques and modern control techniques as well, which has not been present in the available technical literature. Following controllers have been decided to be executed for the control of ES:

    1. To start the work with the most prevalent one i.e., a PI controller, so that other controllers' performances get compared with it.

    2. To design controllers which could observe more number of states for the execution of feedback control. A simple yet efficient Loop-in-Loop construct of inner current and outer voltage control loops using Cascaded-PI controllers in each loop has been designed using two different feedback mechanisms in the form of feedback available from the filtering inductor current, and filtering capacitor current. These mechanisms could help in limiting the inverter current in the event of faults and over-loads. Feedback for the inner loop, using the filtering inductor current is a bit costlier venture to be implemented for the reason that it needs precise measurement of much larger current, compared to that is required in the case of feedback executed through measurement of current flowing through filtering capacitor. Current sensing could accurately be executed through a Hall-effect sensor, which is much cheaper in the case of measurement of current flowing through filtering capacitor due to smaller magnitude.

    3. Lead-Lag controller is the modified and better version of a classical PID controller and can perform better than a PI controller. It has been decided to develop a Lead-Lag controller for ES by canceling unwanted poles and zeros and placing the poles at desired location using the pole placement method. It

has also been decided to design the Lead-Lag controller for the PLL structure also.

4. SVPWM control has not been tried for the application of 1-Φ ES, even though possessing numerous advantages as that compared to SPWM control. It has been decided to try both the control techniques, to be used with the designed Lead-Lag controller, for the purpose of comparative performance analysis of ES.

5. Modern control techniques using State-feedback control are the powerful mechanism of control and having numerous advantages over the conventional means of output feedback control, which has not been accommodated in the available technical literature. It has been decided to implement the same using the more straightforward and tested, Linear Quadratic Regulator (LQR) being optimized through the convex numerical optimization technique called Linear Matrix Inequalities (LMIs), available as a toolbox in the Matlab. An integrator has been added to the so designed LQR, to bring the steady state error to zero.

- Role of PLL structure is crucial for the ES's performance, which has not been given due weightage, and hence it has been decided to identify at least two simple yet robust PLL structures, which could be implemented satisfactorily in the control of ES.

- It has been decided to critically analyze the robustness of these controllers, amidst the wide uncertainties of parametric variations which are being present in the system of ES in the form of variation in,

  - Grid voltage,
  - Grid impedance, present by virtue of impedance of the connecting conductor and is variable due to variation in its length,
  - Variation in the load,
  - Variation in the DC-bus voltage due to variable demand and hence variable charging and discharging pattern of battery.

1.4 Thesis Organization

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, techniques, and pros and cons. Electric spring has been introduced in this chapter. This chapter also presents a review of the present-day status of the active research, research gaps, and objective/motivation for the work's execution and scope in the prevailing research.

Chapter-2 represents the state-of-art and discusses 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 experimental system (test-bench) mimicking the distribution system, loads, and ES and associated aspects that could commonly be used to verify the various controllers 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 grid-tied VSC acting as ES, to generate the phase information, from a considered reference signal.

Chapter-4 presents a PI controlled ES. There has also 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. Two different mechanisms of the inner loop feedback have been considered in the form of (i) current flowing through the filter's inductor and (ii) current flowing through the filter's capacitor. The results derived from these three different strategies have critically been compared and analyzed.

In **Chapter-5**, a Lead-Lag controller has been designed and developed to verify its efficacy in controlling the ES through the implementation of Sinusoidal Pulse Width Modulation (SPWM), and Space Vector Pulse Width Modulation (SVPWM) controlled ES. Their performances have been evaluated to judge the best version of the two.

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 Chapter-4, Chapter-5, and Chapter-6 have been recapitulated. The robustness of these controllers has been tested and analyzed by adapting the more stringent parametric variations in the form of changing grid voltage, load, grid impedance, and DC-bus.

Chapter-8 summarizes the main findings in the form of their significance and the thesis's contribution. Lastly, this chapter also provides a few possibilities and suggestions for the future expansion of this work.