Abstract

ELECTRIC SPRING FOR EFFICIENT DEMAND SIDE MANAGEMENT

Electric Spring (ES) is a custom power device primarily used for the voltage stability/voltage regulation of a consumer's electrical installation. The idea of ES has primarily been derived from its mechanical concept of mechanical spring. As the mechanical spring damps out the shocks and thrust, an ES damps out the oscillations or variations in the voltage across the critical load due to the intermittent nature of renewable energy sources present in the distribution system curb the menace of carbon emission. Electricity demand is increasing day by day, which can only be catered by fossil-based bulk generating sources, polluting the environment. On the other hand, the cleaner option of the same, i.e., RESs are causing pollution of the electrical system itself. Demand-side management (DSM) has emerged to reliably cater to the prevailing demand by managing the load rather than increasing the generation. This work explores the idea of ES as a device commensurating with the concept of DSM in real-time without resorting to ICT aid. The work focused on the exploration of various controllers that has not been tried with the ES.

Prevalent study of the state-of-art 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 10%. Still, the same is not the case with developing countries like India, where voltage regulation commonly hits the limits of 20%.

- Modeled system of ES has been presented as a single-input-single-output (SISO) system in the published literature. In contrast, 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. Considering parametric variations, the voltage of DC-bus, Grid impedance, Grid voltage, and Load requires a robust controller design with a relatively 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, but 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 existing 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 different from a PLL used with the communication signal. PLL and its robustness have not been presented in any 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 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 by using heuristic and meta-heuristic methods, which happens to be an ideal contender for more extensive systems of higher order. The ES system's order never exceeds beyond the 5^{th} order, for which numerical optimization should have been considered, for achieving much higher accuracy and efficacy in the controller's performance.

- Few primary controllers viz., Cascaded PI control, Lead-Lag control has not been tried and tested for the application of the control of ES.

The work in this thesis is organized in a chaptered manner to alleviate and address the presented gaps, as

- **Chapter-1** presents the basic idea of Demand Side Management (DSM), along with its tools, techniques, and pros and cons. ES 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 ES. Further, it gives an idea about the design and development of a basic experimental system (testbed) mimicking the distribution system, loads, and ES and associated aspects that could be commonly 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 ES, to generate the phase information from a considered reference signal.

- **Chapter-4**, presents a PI-controlled ES. There has also been given 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 to limit the current in the case of more significant 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 analysed.

- **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.

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

- **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 analysed by adapting the more stringent parametric variations in 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.