Title

Effect of line impedance on electric spring control

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Effect of Line Impedance on Electric Spring Control

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***Abstract*—The study and development of technologies to facilitate efficient operation of microgrids has recently gained momentum. The Electric Spring is one of the new power electronics based device which can smoothen power and voltage fluctuations caused by load-generation mismatch in a microgrid. Microgrid is a subsystem of the existing power system with a decentralized control and distributed structure. Therefore, its line impedance varies over a wide range. While utilizing the ES as a reactive power compensation device for voltage regulation, the nature of line impedance (inductive or resistive) of the microgrid has not been taken into consideration in the existing control of the ES. This can result in a considerable deviation from the desired performance. This paper investigates the effects of line impedance on voltage regulation operation by the ES. It is proposed that the ES control needs to be altered according to the nature of the system line impedance. This hypothesis has been validated by simulating a small scale grid connected microgrid with resistive and inductive system line impedances.**

***Index Terms*—Electric Spring, Microgrid, Line Impedance**

I. INTRODUCTION

Economic, technological and environmental incentives have initiated remodeling of the existing power system architecture. Research focus is shifting from centralized generation to small-scale distributed energy resources [1]. Proliferation of small-scale decentralized generation such as renewable energy sources (RES) requires parts of the existing network to be capable of operating in isolation. Such sub-systems can offer increased reliability, flexibility and efficiency. These small autonomous regions of power system are called Microgrids [2]. However, increased penetration of RES makes the system susceptible to load-generation imbalance and low physical inertia. As a result, such systems are vulnerable to voltage and frequency fluctuations. Distributed energy storage devices can assist the system in maintaining energy balance [3]. Unfortunately, these devices are very expensive and cause environmental pollution [4].

An alternate way to overcome the problem is by shifting the control paradigm to "load following generation" from "generation following load". This can be achieved by demand side management (DSM), in which the average power consumption of the load is varied as per the input power generation. There are various techniques to achieve this such as load scheduling, on/off loads and load shaving [5]. However, these techniques are incapable of providing continuous dynamic control of loads which is necessary to mitigate fast fluctuations in RES generation [6].

Voltage dependent loads such as electric heating, LED lighting, and small motors loads can vary their power consumption continuously if their supply voltage is varied. This aids in the implementation of Smart Loads (SL), i.e. loads which can reduce power imbalance in the system by adjusting their power consumption [6]. There are be various methods to implement SL in a system, one of which is to connect a power electronic device, called Electric Spring (ES) in series with a voltage dependent load [7]. The ES was introduced as a reactive power compensator which can regulate voltage at a particular node. Later, it was demonstrated that it can reduce energy storage size [4] and be efficient than STATCOM [8]. The ES also offers real power compensation [9], improves frequency profile of a weak system [6], [10], improves input power factor of a system [11] among others. Studies have also been done to observe the effect of load ratios and load variation on the performance of ES [12], [13], [14]. The control of the ES consists of two parts - *phase and magnitude* [7], [9]. In this paper, we focus on the reactive power compensation of the ES for voltage regulation. For reactive power control, ES can have either inductive behaviour or capacitive behaviour depending on the scenario it is facing (over-voltage or under-voltage) [15], [6]. However, the effect of line impedance on the behaviour of ES has not been considered in the studies so far. A microgrid can have a wide variation in the line impedance [16], which is expected to have a significant effect on the ES behaviour.

The main contribution of this paper is to highlight the effect of line impedance on the behaviour of the ES in a microgrid. The performance of the ES under variable line impedences has been evaluated and the ES control is improvised to suit the nature of system line impedance. Section II gives a brief overview of microgrid line impedance and working principle of the ES. It is followed by a theoretical analysis of change in phase control of the ES with line impedance in Section III. Simulation results are provided in Section IV by simulating ES in a grid connected microgrid which validates that ES control needs to be changed based on system line impedance. The conclusions of this work are then provided in Section V.

II. BACKGROUND

A. Microgrid Line Impedance

Microgrids are sub-systems which aid in realizing the emerging potential of renewable energy based distributed gen-

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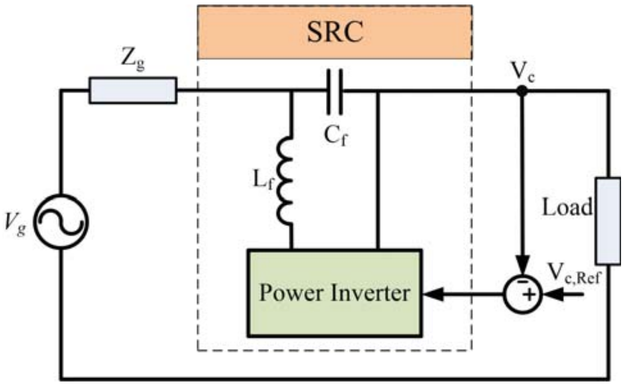
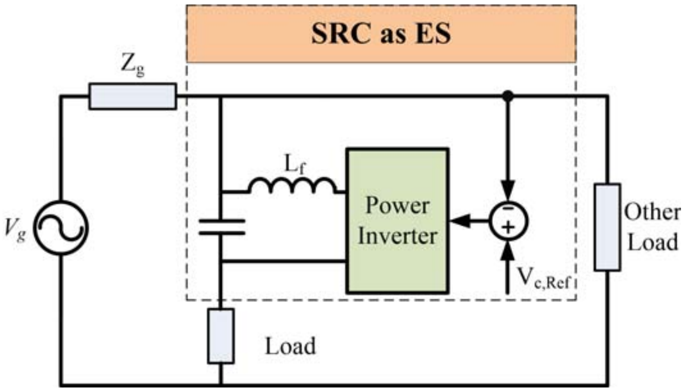


(a) Traditional SRC



(b) Electric Spring as SRC

Fig. 1. Traditional SRC vs Electric Spring SRC

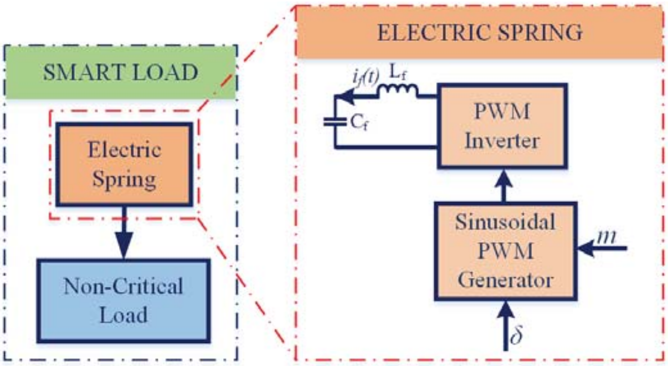


Fig. 2. Smart Load

eration. The major components of a microgrid are a small scale distributed generation (such as RES) with power electronic interface, distributed loads and spinning energy reserves (generally energy storage devices). Due to their smaller structure, they are expected to have resistive line impedance. However, the R/X ratio can vary significantly across the microgrid. For example, in a benchmark low voltage microgrid network developed by CIGRE, the R/X ratio of the line varies from 39.25 to 1.423 [16]. Thus, it is important to study the behaviour of the ES in a system with different line impedances.

B. *Electric Spring Working Principle*

Electric Spring (ES) is a series reactive power compensator (SRC) with a subtle change in its control strategy. Unlike the traditional SRC, which controls the output voltage of the compensator, the ES controls the input voltage as shown in Fig. 1 [7].

As shown in Fig. 1, the ES should be connected in series with a load which can tolerate voltage fluctuations while delivering satisfactory performance. Such loads are termed as non-critical loads. Another requirement from such loads is that their power consumption should vary with their supply voltage, i.e. they need to be voltage dependent loads such as water/space heater, lighting systems (especially, LEDs), small motors loads (fan, ovens, dishwashers, dryers), among others [6]. On the other hand, there are certain sensitive loads, which cannot tolerate voltage and power fluctuations for their satisfactory performance. Such loads are referred to as critical loads. The series combination of the ES with non-critical loads is termed as smart load. The ES can be modeled as a controlled voltage source, which modifies its voltage output as per the requirement. Fig. 2 shows the ES as a PWM inverter. By controlling the injected voltage, the ES can vary the voltage across the non-critical load, which in turn will vary the smart load power consumption and bridge the gap between power supply and power demand.

Fig. 3 shows the ES implemented in a grid connected microgrid. The microgrid consists of two loads – one critical and one non-critical – and is fed by a intermittent renewable energy source.

$$P_{in} = P_{grid} + P_{RES} \tag{1}$$

$$P_{load} = P_{CL} + P_{NCL} \tag{2}$$

$$\overrightarrow{V_c} = \overrightarrow{V_{es}} + \overrightarrow{V_{nc}} \tag{3}$$

where P_{in} is the total real power input to the microgrid, P_{grid} is the real power input from the grid, P_{RES} is the real power input from the renewable energy source, P_{CL} is the real power consumption of the critical load, P_{NCL} is the real power consumption of the non-critical load, P_{load} is the total real power consumption of loads.

ES's control objective is to regulate the critical load voltage at the reference voltage. Voltage fluctuation occurs in a microgrid when there is a generation-load mismatch which can occur in the following two ways:

1. Under-voltage: This case arises when the power supply is insufficient for the loads ($P_{in} < P_{load}$). This causes the critical load voltage to fall. Therefore, the ES needs to boost the voltage.

2. Over-voltage: This case arises when the power supply is more than load consumption ($P_{in} > P_{load}$). This causes the critical load voltage to rise. Hence, the ES needs to reduce the voltage.

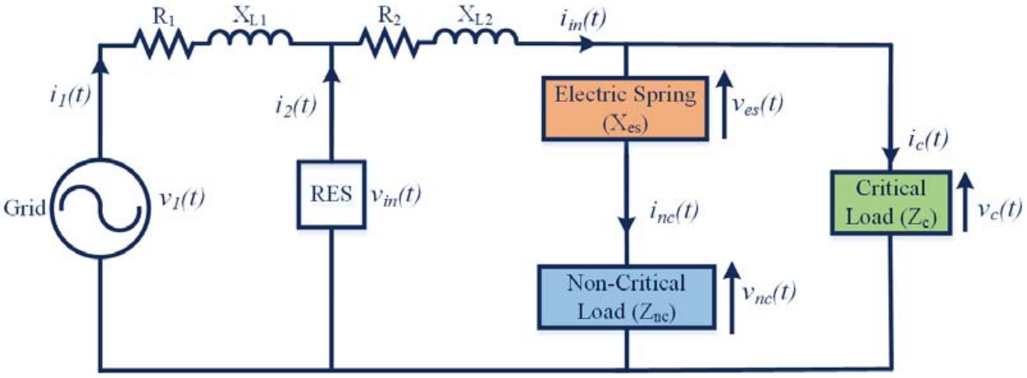


Fig. 3. Electric Spring in grid connected microgrid

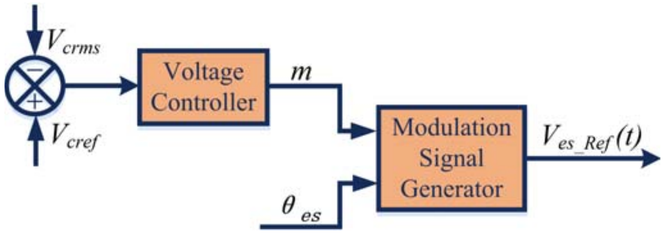


Fig. 4. Electric Spring Control

For this study, we have only considered ES with reactive power compensation. Fig. 4 shows the control algorithm for ES. The generated voltage, V_{es} has two components - *magnitude and phase*. The magnitude of V_{es} is controlled by voltage controller to ensure that the critical load voltage is maintained at the reference value. In order to limit the compensation offered by ES to reactive power compensation only, it is ensured that the injected voltage is in quadrature with the current, $i_{nc}(t)$, flowing through it as shown in equation (4).

$$\overrightarrow{V_{es}} \perp \overrightarrow{I_{nc}} \tag{4}$$

Whether V_{es} will lead or lag I_{nc} depends on the scenario - under-voltage or over-voltage and the system line impedance, as explained in the following section.

III. THEORETICAL ANALYSIS

Since ES's control is restricted to reactive power control only, the ES will act as an inductor or a capacitor when it is in operation as in equation (5). The circuit shown in Fig. 3 was analysed for a resistive and an inductive line impedance. Equation (6) was used to plot the variation of critical load voltage with respect to ES reactance. All the loads were assumed to be linear resistive-inductive (RL) loads.

$$Zes = \begin{cases} jXes, & \text{ES as inductor} \\ -jXes, & \text{ES as capacitor} \end{cases} \tag{5}$$

$$V_c = \frac{V_1((Z_{nc}+jX_{es})\|Z_c)}{((Z_{nc}+jX_{es})\|Z_c)+Z_1+Z_2} + \frac{I_2 Z_1((Z_{nc}+jX_{es})\|Z_c)}{((Z_{nc}+jX_{es})\|Z_c)+Z_1+Z_2} \tag{6}$$

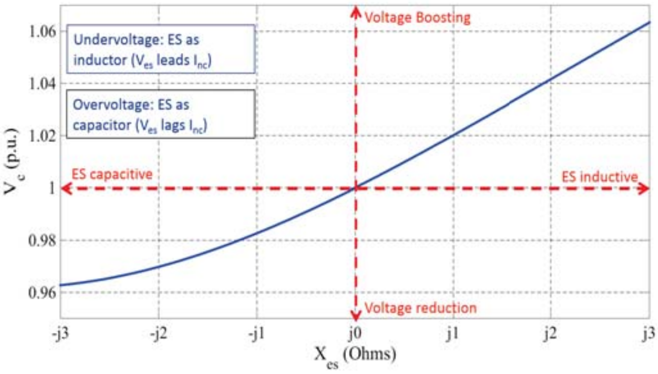


Fig. 5. Variation of critical load voltage with ES reactance for resistive line impedance

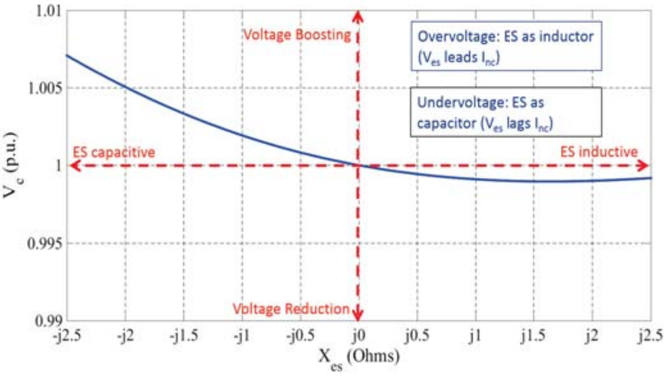
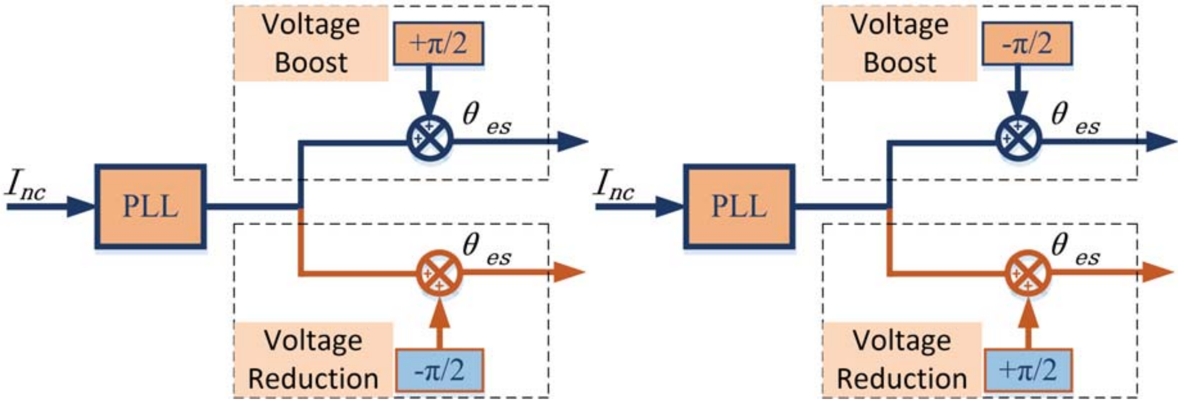


Fig. 6. Variation of critical load voltage with ES reactance for inductive line impedance

where $Z_1 = R_1 + jX_{L1}$ and $Z_2 = R_2 + jX_{L2}$

1. Resistive Line Impedance: The line impedance was kept as resistive with negligible reactance. The critical load voltage,V_c was plotted with respect to various values of ES reactances using equation (6). Fig. 5 shows that when the ES acts as an inductor, the critical load voltage increases with increasing reactance. This can be explained by the fact that by increasing X_{es} magnitude the net smart load impedance rises, which decreases the input current. Hence, the line impedance



(a) (b)

Fig. 7. ES Phase Control for (a) resistive system line impedance and (b) inductive system line impedance

drop decreases, thereby boosting the critical load voltage. When the ES acts as a capacitor, for a low capacitance, critical load voltage is observed to decrease. This happens till $X_{es} = X_{nc}$, after which an increase in X_{es} will boost V_c.

Consequently, we can conclude that for a system with resistive line impedance, ES needs to act as a capacitor for the over-voltage scenario. For the undervoltage scenario, ES can act as either inductor or capacitor. However, it is more efficient to operate the ES as an inductor for voltage boosting because for the same magnitude of X_{es} (or V_{es}) an inductor offers more voltage boosting than that by a capacitor. This control technique is termed as R-Control.

2. Inductive Line Impedance: The line reactance was kept as inductive with negligible resistance. Fig. 6 shows the effect of ES reactance on critical load voltage, V_c. As it can be observed, V_c decreases only when ES is an inductor. Therefore, for over-voltage scenarios, ES needs to act as an inductor, unlike a system with resistive line impedance, where voltage reduction is only offered by ES as a capacitor. For undervoltage scenarios, ES can act as a capacitor or as an inductor. However, it is more efficient to operate ES as a capacitor for voltage boosting. This control technique is termed as L-Control. This can be explained by the fact that the quadrature component of the current flowing through the line will affect the terminal voltage.

Hence, the ES control cannot remain the same for the entire range of R/X ratio of the line impedance and might be detrimental unless controlled properly. Fig. 7 shows the two different control schemes for system with inductive and resistive line impedances. The proposed control schemes are validated by simulating ES in a grid connected microgrid.

TABLE I
SYSTEM PARAMETERS

Grid Voltage	$245V$
System Frequency	$50Hz$
Resistive Line Impedance	$0.625\Omega/km$
Inductive Line Impedance	$j0.191\Omega/km$
Non-Critical Load	$8 + j4\Omega$
Critical Load	$16 + j8\Omega$

IV. RESULTS AND DISCUSSIONS

The microgrid shown in Fig. 3 was simulated in MATLAB/*Simulink* environment with the parameters given in Table I. The grid voltage is set at 245V rms, 50Hz. One-minute solar irradiance data for 7th January 2016 collected by the Solar Energy Research Institute of Singapore (SERIS), are employed to create RES current profile shown in Fig. 8. These were measured in Singapore (latitude of 1.3026°, longitude of 103.7729°, tilted angle of 10° and azimuth angle of 180°). For the study, solar data from 01:15 pm to 01:20 pm was taken. The voltage controller is implemented using a basic Proportional-Integral (PI) controller. For phase control, a second order generalised integrator (SOGI) based phase locked loop (PLL) is used to measure non-critical load current phase. ES phase control is designed as shown in Fig. 7. The simulation was conducted for two systems, one with resistive line impedance and another inductive line impedance. For each system, the simulation was run in three parts – without ES, ES with L-Control and ES with R-Control. The five minutes solar irradiance profile was repeated for each part. All the loads are assumed to be linear RL loads.

Fig. 9 shows the results for system with resistive line impedance. Without ES the critical load voltage follows the fluctuations in RES current. When ES is switched ON with L-Control, the voltage fluctuations deteriorate. On changing the control to R-Control, the critical load voltage is regulated to 230V by the ES. The ES reactive power is positive and negative for voltage boosting and voltage reduction action respectively. This proves that the ES behaves as an inductor

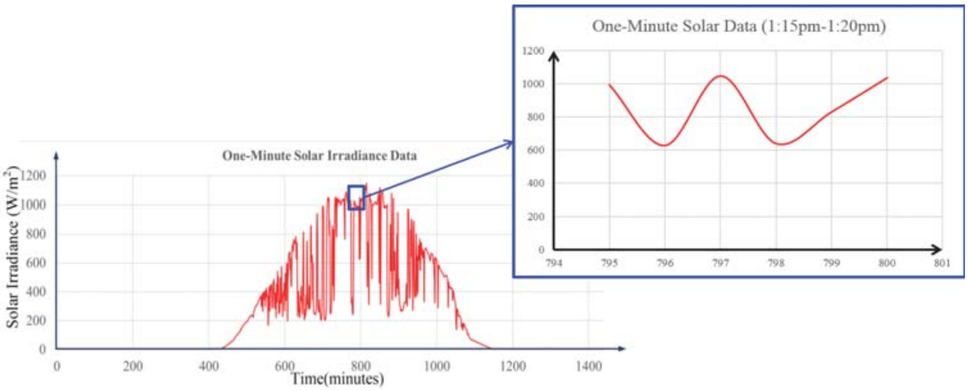


Fig. 8. One minute solar irradiance data for 24 hours

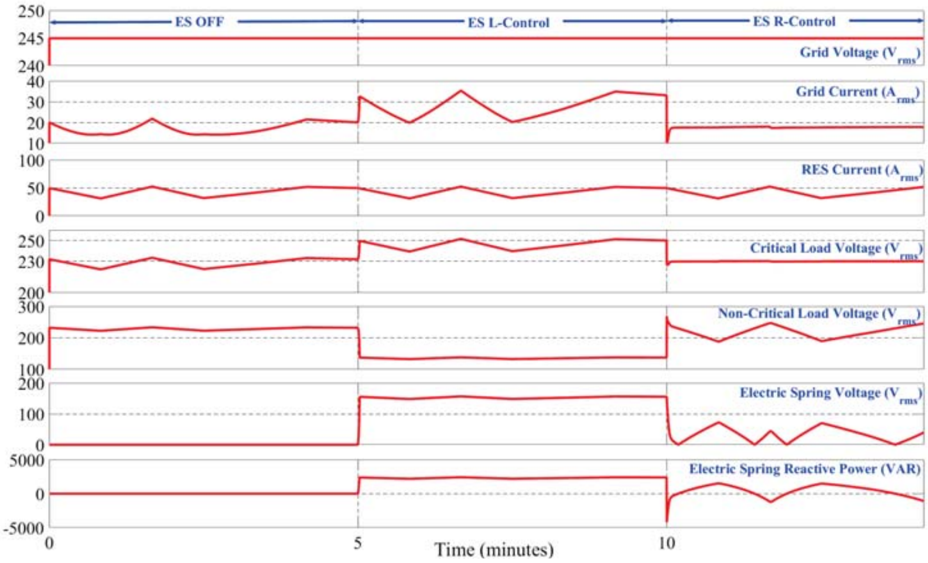


Fig. 9. Simulation Results for System with Resistive Line Impedance

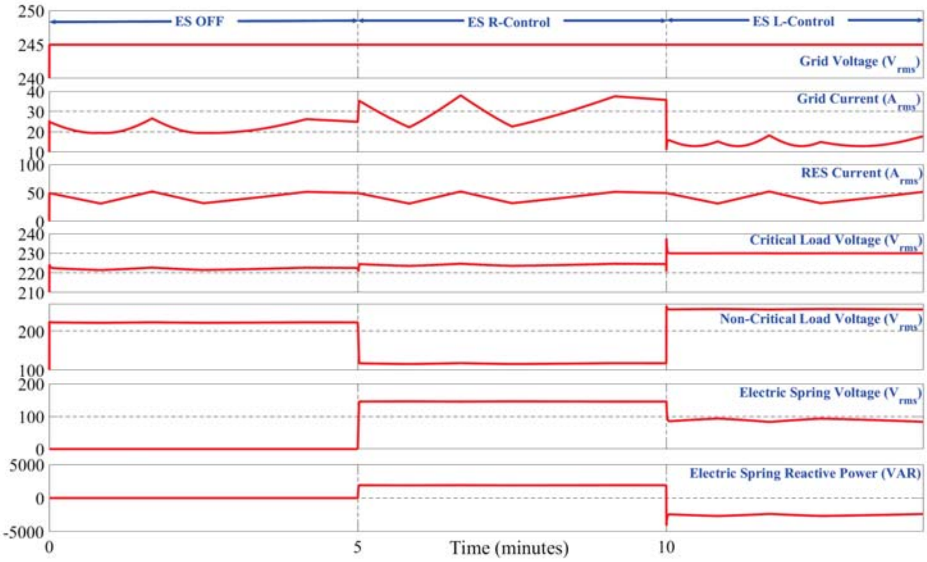


Fig. 10. Simulation Results for System with Inductive Line Impedance

for under-voltage scenario and as a capacitor for over-voltage scenario.

Fig. 10 shows the results for system with inductive line impedance. Similar to the previous system, the critical load voltage fluctuates when ES is OFF. Turning ON ES with R-Control, it was observed that ES is unable to boost the critical load voltage to 230V. When the ES control is changed to L-Control, the critical load voltage is tightly regulated at 230V. From the ES reactive power values, it can be inferred that ES behaves as a capacitor for voltage boosting and as an inductor for voltage reduction.

V. CONCLUSIONS

This paper highlights the anomaly in using the same electric spring control for the entire range of grid impedances. From the theoretical analysis presented in this paper, it is demonstrated that the ES control reverses as the system line impedance changes from resistive to inductive. In a system with resistive line impedance, the ES acts as a capacitor for under-voltage scenario and as an inductor for over-voltage scenario, which is opposite to what happens in a system with inductive line impedance. Simulation study is carried out with a small scale microgrid validates the theoretical claim. The application of the ES lies in small decentralised systems where line impedance varies over a broad spectrum. Therefore, the ES design should be customised as per the line impedance it sees at the point of connection. Another alternative is to develop a flexible control for the ES which can adapt to different line impedances, which is currently under investigation.

ACKNOWLEDGMENT

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