Electric Spring Enhanced Decoupled Dual Function Operation: Bus Voltage Controller and Renewable Energy Grid Integration

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Abstract

Electric Springs (ES), a converter topology connected in series with non-critical loads, has been recently developed to restore bus voltages to their reference value in case of voltage sag/swell by injecting/absorbing reactive power into/from grid. In this paper, a dual-function ES is proposed with an enhanced decoupled controller, offering additional capability of Renewable Energy Sources (RES) grid integration. Hence, the proposed ES controller is capable of simultaneously injecting active power, extracted from a PV arrays, into grid and mitigating bus voltage fluctuations. Simulation results verify the proposed ES effectiveness when varying irradiance level and bus voltage states.

Variables Nomenclature

- $V_s$: Nominal feeder voltage
- $V_o$: Non-critical load voltage
- $V_{es}$: ES injected voltage
- $S_i$: Grid apparent power
- $S_{nc}$: Non-critical load apparent power
- $S_c$: Critical load apparent power
- $I_s$: Non-critical load current – Smart load current
- $Z_{nc}$: Non-critical load impedance
- $Z_c$: Critical load impedance

I. Introduction

Growth in energy demand together with the need to reduce the environmental impact of fuel consuming generation stations resulted in increasing penetration of renewable energy sources (RES). Such resources can be utilized on a large scale, such as wind farms connected to transmission systems, or on a small scale as in the case of wind turbines connected to micro-grids. [1,3]

However, the power obtained from such sources has a high degree of variability and uncertainty due to their dependency on multiple environmental variants [1, 2]. Concerns about voltage stability, which is directly related to power system stability, have increased lately due the widely distributed intermittent renewable energy sources among the utility grid. However, it’s difficult for power companies to instantaneously predict and control the feeder voltage and power in the entire grid [1, 3].

In ANSI Standard C84.1 [4], acceptable steady-state voltage ranges, at both the utility service entrance and the point of connection of end-use equipment, are shown in Table I.

Overvoltage above 10% can immediately cause equipment failure while under voltage below 10% usually leads to excessive current demands, especially for equipment that has a controlled output [4].

In micro-grids, feeder voltage fluctuations, caused by large RES, are usually mitigated by introducing dynamic voltage restorers (DVR) into the system in order to inject a compensating series voltage. However, being applied at the transmission level, these devices are costly and demand complicated protection system when compared to voltage compensators introduced at the distribution level which features lower voltage and current rating components [4].

The concept of Electric Spring (ES) was first introduced in [5-16], featuring a new smart grid terminology known as “Input Voltage Regulator” which classified loads, connected to the distribution system, into critical and non-critical loads. The ES basic idea is to provide stable voltage and in turn power to critical loads on the expense of non-critical loads since the latter endure a wider range of voltage fluctuation. Consequently, these non-critical loads will have voltage and power profiles that follow the generation profile, hence the entire bus voltage will be regulated. With such methodology, the ES can be used as a decentralized voltage controller that

| Table I. ANSI C84.1 voltage ranges. Range A is for normal conditions, and Range B is for emergency or short-time conditions [2] |
|-------------|-------------|
| **Service Voltage** | **Utilization Voltage** |
| Range A | 114–125 | 108–125 |
| Range B | 110–127 | 104–127 |
can improve system power quality at the distribution level with its reduced rating device [5-16].

In this paper, a new control scheme is proposed, offering the classical ES a decoupled dual-function capability of interfacing a RES to the grid, together with its inherited bus voltage regulation function, utilizing only a single converter. Hence, the proposed ES is able to extract maximum power from a local generated renewable source (PV arrays in the simulated case) at different environmental conditions, inject it to grid and meanwhile regulate the bus voltage for different voltage fluctuations.

This paper is divided into three sections: the first is the classical ES system illustrating the system configuration, principle of operation, control algorithm and simulation results. The proposed ES system with the capability of integrating renewable energy sources to grid is demonstrated in section two with system configuration, control algorithm and simulation results presented. Section three offers a summary and a conclusion for the presented system.

II. Classical Electric Spring system:

In this section, the system under consideration is investigated first without ES then with the classical ES to verify its effectiveness in stabilizing the bus voltage under different voltage fluctuations. System configuration, classical ES operation principle and its control algorithm are illustrated, followed by system simulation results.

A. System block diagram:

The block diagram of the considered system is shown in fig. 1, where a weak grid and a renewable energy source (wind turbine in this case) are the power sources in the network [17-18]. Two types of loads are connected; a critical Load (CL) which is highly sensitive to voltage variations and a non-critical load (NCL) which allows a wide range of voltage variation, hence will be connected in series to the applied ES. ES is operating as bus voltage regulation device, converting the series connected load into what is called Smart Load (SL) [5-9]. In other words, this series non-critical load will have a voltage profile proportional to the unregulated grid voltage profile, thus regulating the entire bus voltage [5-9]. Table II presents the specifications of the classical system under investigation.

B. Operation principle

The main function of classical ES is to maintain the feeder voltage (Vs) at its reference value with minimal ripple. The feeder voltage is governed by (1) as follows;

$$\bar{V}_s = \bar{V}_o + \bar{V}_{es}$$

(1)

Grid apparent power ($S_g$) is divided among critical and non-critical loads as follows;

$$S_g = S_{nc} + S_c$$

(2)

Hence;

$$S_g = \frac{\bar{V}_o^2}{Z_{nc}^*} + \frac{\bar{V}_{es}^2}{Z_c^*}$$

(3)

Substituting (1) into (3);

$$S_g = \frac{(\bar{V}_o - \bar{V}_{es})^2}{Z_{nc}^*} + \frac{\bar{V}_{es}^2}{Z_c^*}$$

(4)

where $Z_{nc}^*$ and $Z_c^*$ are the conjugate of the non-critical and critical load impedances respectively. The current in the non-critical load branch is described by

$$I_s = \frac{(\bar{V}_o - \bar{V}_{es})}{Z_{nc}}$$

(5)

From (5), it is clear that the injected voltage ($V_{es}$) has a direct effect on the non-critical load branch current ($I_s$) for constant feeder voltage ($V_o$). Hence, the feeder voltage ($V_o$) can be kept constant using a certain compensation voltage value ($V_{es}$). This value can be either positive for voltage sag compensation, or negative for voltage swell compensation. This is demonstrated in the vector diagram shown in fig. 2 parts (a) and (b). The former shows ES operation during voltage sag whereas the latter demonstrates ES performance under voltage swell in order to regulate the feeder voltage in both cases.

![Block diagram of classical system under investigation](image)

**Table II: Specifications of classical system under investigation[6]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Rating</td>
<td>220 V, 50 Hz</td>
</tr>
<tr>
<td>Grid impedance</td>
<td>0.51 Ω + 16.3 mH</td>
</tr>
<tr>
<td>P=250W, Q is varied</td>
<td></td>
</tr>
<tr>
<td>1100 VAR → bus voltage sag</td>
<td></td>
</tr>
<tr>
<td>467 VAR → bus voltage swell</td>
<td></td>
</tr>
<tr>
<td>2 km feeder</td>
<td>0.1 Ω + 2.4 mH</td>
</tr>
<tr>
<td>1 km feeder</td>
<td>0.1 Ω + 1.22 mH</td>
</tr>
<tr>
<td>Non critical Load</td>
<td>50.5 Ω</td>
</tr>
<tr>
<td>Critical Load</td>
<td>53 Ω</td>
</tr>
</tbody>
</table>
D. Simulation results

To demonstrate the ES effect on bus voltage, three test cases are applied to the system shown in fig. 1. These cases include normal bus voltage conditions, voltage sag and voltage swell. These tests are simulated by changing the reactive power (VAR) consumption of the applied renewable energy resource (RES). VAR consumption is set to be 467 VAR during normal voltage operation, 1100 VAR under voltage sag and 110 VAR under voltage swell.

Under these three cases, the considered system is simulated using two scenarios; (i) without ES, achieved by closing the bypass switch and (ii) with ES, performed by opening the bypass switch as shown in fig. 1. Simulation results show the feeder voltage condition at these two scenarios for different voltage fluctuations as shown in fig. 4.

Fig. 4 (a) shows the feeder voltage when no ES is applied. At starting point, normal condition is maintained, where RES VAR consumption is set to 467 VAR. Thus, power balance occurs and the feeder voltage is 220 Vrms. For t=2 s till t=9 s, VAR consumption is set to 1100 VAR which causes voltage sag condition with a drop in feeder voltage to 203 Vrms. For t=9, the voltage is restored to normal condition till t= 11s. For t=11s till t=18 s, the feeder is in voltage swell condition corresponding to RES consuming 110 VAR. In this case, the feeder voltage rises to 228.5 Vrms. Finally, for t=18s till t=20s, the voltage is restored back to normal condition.

Fig. 4 (b) shows the second scenario with the three test cases applied. The ES is now connected in series with the non-critical load and operates as a feeder voltage regulator device.

Finally, if the injected voltage $V_i$ is equal to the feeder voltage $V_f$, the non-critical load current will decrease significantly and the ES will lose its ability to regulate the feeder voltage.

C. Control algorithm

The control algorithm applied by the classical ES, for bus voltage regulation, is shown in fig. 3 [6]. The feeder rms voltage is maintained at its reference value (220 V) using a PI controller which controls the switching of the inverter connected in series with the non-critical load [5-10]. The controller output can define the state of the ES as follows;

- Voltage Sag $\rightarrow$ Capacitive ES Mode
- Voltage Swell $\rightarrow$ Inductive ES Mode

Since the feeder voltage level can be directly controlled by controlling reactive power injected/consumed by loads, the ES controller basic idea is to inject a voltage shifted $\pm 90^\circ$ from the non-critical load branch current ($I_L$). For voltage sag case, the ES is in capacitive mode and the injected ES voltage lags the non-critical load current by $90^\circ$. In other words, the capacitive ES mode forces the ES to inject reactive power to the feeder to compensate for the voltage drop. On the other hand, in voltage swell case, the ES acts in inductive mode and consumes reactive power from the feeder to mitigate the voltage rise. Hence, in this case, ES injects a voltage that leads the non-critical load current in branch by $90^\circ$ [6]. The angle of the branch current is obtained via a PLL to be added $\pm 90^\circ$ in order to obtain the injected ES voltage angle as follows;

$$\phi_v = \theta_i \pm 90^\circ \quad (6)$$

where $\phi_v$ and $\theta_i$ are the injected voltage and the branch current angle respectively. The controller output determines the modulation index used to compensate for feeder fluctuations.
with controller reference set to 220 Vrms. Similarly, the reactive power consumption of the RES is varied to simulate the three test cases (normal voltage level, voltage sag and voltage swell). The simulation is started at normal feeder voltage level and the ES has no effect on system. At \( t = 2 \) s, a voltage sag case occurs till \( t = 10 \) s. Now with the ES applied, the feeder voltage is regulated to reach 219.8 Vrms, unlike the 203 Vrms achieved by the system without ES during the same condition. A noteworthy point is that the transient voltage drop during sag condition with ES installed doesn’t exceed 5% of the rated feeder voltage. At \( t = 10 \) s, the normal feeder voltage level is restored till \( t = 15 \) s. A transient voltage rise occurs due to the previous ES operation mode, which doesn’t exceed 5% of the rated feeder voltage. For \( t = 15 \) s till \( t = 25 \) s, the voltage swell case is simulated where ES was able to regulate the feeder voltage to 221.2 Vrms. Voltage transients occurs due to previous ES operation mode which is also within the limits of 5% of rated voltage. At \( t = 25 \) s, normal voltage condition is restored.

Hence, applying ES in series with non-critical loads, has the merit of regulating feeder voltage and reducing voltage transients during various voltage fluctuations.

### III. Proposed Dual-Function Electric Spring

In this section, a system configuration and control strategy are proposed to establish a dual-function ES that, besides being able to regulate the feeder voltage, can inject the extracted maximum PV power from a local unit like a residential roof mounted PV system into the grid simultaneously. The proposed ES is simulated under the same test cases, applied in the previous section, to demonstrate the effectiveness of the proposed decoupled dual-function control scheme.

### A. Proposed system configuration:

Figure 5 shows the modified system block diagram with specifications listed in Table III. The proposed ES features a PV source grid-integration capability while the voltage regulation aspect is maintained. Hence, it has two functions; the first main function is to regulate the feeder voltage and the newly added function is to extracted PV maximum power and then inject it into grid. This is done via a two-stage single-phase topology [19-21], compromising a boost DC/DC converter followed by a single-phase full bridge inverter. The former is used to achieve PV MPPT and step up the PV voltage to 200 V at the inverter DC-link, while the inverter transfers the extracted PV power to the grid. Three series PV panels are connected, each with the characteristic curves shown in fig. 6.

<table>
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<tr>
<td>Grid impedance</td>
<td>0.51 Ω + 16.3 mH</td>
</tr>
<tr>
<td>Renewable Energy Source</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( P = 250 \text{W} ), ( Q ) is varied</td>
</tr>
<tr>
<td></td>
<td>1100 VAR ( \rightarrow ) bus voltage sag</td>
</tr>
<tr>
<td></td>
<td>467 VAR ( \rightarrow ) bus voltage is 220 V</td>
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</tr>
<tr>
<td>Non critical Load</td>
<td>50.5 Ω + 50 mH</td>
</tr>
<tr>
<td>Critical Load</td>
<td>70 Ω</td>
</tr>
<tr>
<td>PV array</td>
<td>Panel : SunPower SPR-X20-250</td>
</tr>
<tr>
<td></td>
<td>Peak Power per module ( = 250 \text{W} )</td>
</tr>
<tr>
<td></td>
<td>Series Panels = 3, ( V_{mp} = 37 \text{V} )</td>
</tr>
<tr>
<td></td>
<td>Total power of the array = 750 W</td>
</tr>
</tbody>
</table>
B. Proposed control strategy:

An enhanced performance control scheme is proposed, as shown in fig. 5, enabling the modified ES to regulate the feeder voltage and supply electrical power to loads, when being integrated in weak grid where loads are located far away from the generation. The control strategy is divided into five sub-control loops:

1. Feeder voltage regulation loop.
2. PV MPPT.
3. DC-link stabilizer loop.
4. Active power injection loop.
5. Grid-interface control loop.

In the first loop, the feeder voltage is forced to follow a reference voltage of 220V\textsubscript{ref} via a PI controller which determines the amount of voltage (V\textsubscript{d}) to be injected with an angle shifted ±90° from the non-critical load current. This results in a flow of reactive power from/to the ES, hence the feeder voltage is regulated.

The newly added function to the proposed dual-function ES is to track PV maximum power and inject into the grid. Hence, a MPPT control loop is required to extract the maximum available PV power [22-27]. This loop implements Perturb & Observe (P&O) MPPT algorithm, with the flowchart shown in fig. 7. This MPPT technique has simple implementation and acceptable performance during environmental changes [28, 29]. The third control loop stabilizes the DC-link voltage (V\textsubscript{dc}) at 200V to guarantee the power balance at the inverter DC-link, hence PV power can be transferred to the inverter AC-side. However, this loop should be robust enough to keep the DC-link voltage within the limits of ±10 % for the ES to work properly [30, 31]. A PI controller is applied in this loop.

![Figure 6: PV panel SunPower SPR-X20-250 characteristics. (a) Power-Voltage curve, (b) Current-Voltage curve.](image)

![Figure 7: Flow chart of P&O MPPT algorithm][21]

to generate a control signal proportional to the DC-link compensation power i.e. the power required by the DC-link capacitor to stabilise the DC-link voltage at its reference value [21, 32 and 33]. This power is subtracted from the maximum extracted PV power to produce the reference value of the power available to be injected into the grid. Hence, the active power injection loop is mandatory to force the ES active power to match the reference injected grid power. This is done by a PI controller which determines the amount of voltage (V\textsubscript{d}) to be injected in phase with the non-critical load branch current. After calculating ES voltage real and imaginary terms (V\textsubscript{a} and V\textsubscript{q} respectively) using the first and fourth loops respectively, a dq/αβ transformation is applied to generate the inverter reference voltage. Since the proposed ES is applied in a single-phase system, the reference voltage is the calculated α reference command and the β reference command is discarded. Finally, the fifth loop forces the ES voltage to match this reference, hence the active power, available at the inverter AC-link, is injected into grid and PV-grid interface is achieved. However, some problems arise when using power electronic devices for PV-grid integration. These may include high total harmonic distortion (THD) and DC voltage injection. The harmonic current problems can be minimized using L-C filter at the grid side and a proportional resonant controller in the fifth loop. The latter has proven ability to eliminate the steady state error if correctly tuned [34, 35].

C. Simulation results:

To demonstrate the proposed ES effectiveness in regulating the feeder voltage and meanwhile integrating a RES to grid, the proposed system, shown in fig. 5, is simulated under four test scenarios. The first scenario is achieved at solar irradiance of 1000 W/m\textsuperscript{2} for multiple feeder voltage fluctuations, then the three remaining
scenarios occur for a step change in irradiance, from 1000W/m² to 700 W/m² during (i) Normal feeder voltage level (ii) Voltage sag case, and (iii) Voltage swell case.

The first scenario simulation results are shown in figure 8 parts (a), (b) and (c), presenting feeder voltage behavior, reference and actual ES active power to be injected into grid, and the DC-link response respectively. At simulation start, the DC-link capacitor is uncharged which causes fluctuations in the feeder voltage and is rapidly mitigated by the ES itself. From simulation start till $t=5$ s, feeder voltage is at the normal level (220 V), hence ES only function is to regulate DC-link voltage ($V_{dc}$) and inject active power into grid. At $t=5$ s, voltage sag is simulated by varying RES reactive power consumption to 1100 VAR. The proposed ES now has three main functions; (i) regulate the feeder voltage to 220 V (ii) maintain $V_{dc}$ to 200 and (iii) inject active power into grid. The sag case runs for 10 s simulation time and through that period the proposed ES achieved a regulated feeder voltage at 218.8 V. From $t=5$ s and for 10 s simulation time, the feeder voltage is restored back to normal voltage level. The rise in the feeder voltage is caused by the previous ES operation mode. However, this voltage rise doesn’t violate the voltage quality standards of 10% of nominal feeder voltage [1-4]. From $t=25$s till the end of simulation, voltage swell case is simulated by setting RES VAR consumption to 110 VAR. By the help of the proposed ES, the voltage is dampened to meet the voltage quality standards. For all cases in this scenario, the DC-link voltage is maintained at 200V and the injected grid power followed the available power reference.

The second test scenario is performed to validate the proposed ES capability to adapt with sudden changes in solar irradiance in case of normal feeder voltage level. System simulation at 1000 W/m² ran for 12.5 s then followed by a step decrease in irradiance to 700 W/m² till $t=25$ s. Simulation results are shown in fig. 9. It’s clear, from fig. 9 (b), that the maximum extracted PV power decreases with irradiance decrease. Moreover, the available ES power to be injected into the grid is less than the extracted PV power by an amount required to compensate for DC-link voltage variations (i.e. DC-link compensation power). This test proves that the proposed ES can successfully extract PV MPP and injects it into

![Figure 8: Proposed ES dynamic response, at 1000 W/m², for different voltage fluctuations, (a) feeder voltage, (b) ES reference and injected power, (c) DC-link voltage](image)

![Figure 9: Proposed ES dynamic response at normal voltage condition for step change in irradiance (a) feeder voltage, (b) PV extracted power and ES reference and injected active power and (c) DC link voltage.](image)
grid while having no impact on the feeder voltage even under sudden changes in irradiance. The third test scenario is performed to verify the proposed ES capability under sudden irradiance changes, when the feeder voltage is under sag condition. First, solar irradiance is set to 1000 W/m² and for 5 s, the feeder voltage is set to 220 Vrms. At t=5s, a voltage sag condition is applied while at t=15 s, the solar irradiance is reduced to 700 W/m² and the sag condition is maintained. Simulation results are presented in fig. 10. Figure 10 (a) shows the feeder voltage regulated by the proposed ES under variations in voltage and irradiance level. Figure 10 (b) shows the maximum PV power extracted by ES at different irradiance levels and how this power is not affected by the voltage sag condition. Moreover, this figure verifies the match between the ES grid injected power with its reference. Figure 10 (c) shows the stabilized DC-link voltage response even under voltage and irradiance variations.

The fourth test scenario is a repetition of the third scenario but when the feeder is in the voltage swell condition. Similarly, solar irradiance is set to 1000 W/m² and the feeder voltage is set to 220 Vrms for 5 s, then voltage swell condition is applied. At t=15 s, the solar irradiance is changed to 700 W/m² while maintaining the swell condition. Simulation results are shown in fig. 11. Figure 11 (a) shows the regulated feeder voltage response under voltage and irradiance changes. Figure 11 (b) shows the maximum power extracted from the PV array at both irradiance levels and how this power is not affected by the voltage swell condition. The grid power injected by the proposed ES is also presented following its reference value. Figure 11 (c) shows the stable DC-link voltage response to voltage and irradiance variations. Finally, simulation results’ analysis validates the decoupled control strategy proposed for the dual-function ES. Any change in irradiance level has no impact on the feeder voltage regulation loop meanwhile any change in feeder voltage has no effect on PV extracted power.

IV. Conclusion:
A dual function operation of the recently developed has been proposed. The presented decoupled control strategy enhances the ES performance. In addition to the classical bus voltage regulation function, the proposed decoupled control enables the ES to inject local available PV power to grid without violating the bus voltage regulations. The
proposed dual functionality has been validated by simulation, during various bus voltage fluctuations and under solar irradiance variation conditions.

References