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2019

Qi, Y., Yang, T., Tang, Y., Potti, K. R. R., & Rajashekara, K. (2019). A transformless electric spring with decoupled real and reactive power control. 2019 IEEE 4th International Future Energy Electronics Conference and ECCE Asia.

<https://hdl.handle.net/10356/100063>

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A Transformless Electric Spring with Decoupled Real and Reactive Power Control

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Abstract—The electric spring has emerged as a promising technique to stabilize electrical grids with high penetration of renewable energy sources. In response to the grid frequency deviation, electric springs can flexibly regulate the noncritical load power. However, the previous versions of electric springs either suffer from the coupling effect between real and reactive powers, or require associated energy storage systems, or need an extra low-frequency transformer for the isolation purpose. To overcome these shortcomings, a transformless electric spring and its associated control strategy are proposed in this paper. The proposed electric spring can independently regulate the real and reactive power without using batteries for maintaining the DC-link voltage or handling power flow. Finally, real time hardware-in-loop (HIL) simulation results are provided for verification.

Keywords—microgrids; frequency regulation; electric spring; demand respond; real and reactive power control.

I. INTRODUCTION

The increasing use of power converters has brought both opportunities and challenges for future power grids. Despite the flexible integration of renewable energy resource (RES), numerous concerns also arise with respect to the converter-dominated power system. One particular worry is about the ever-decreasing system inertia, which happens as the result of continuously replacing generators with inertialess power converters. The reduction of system inertia makes it more challenging to regulate the system frequency, especially in terms of the rate of change of frequency (RoCoF) and the frequency nadir [1]. It is known that a significant frequency deviation will seriously influence the normal operation of critical loads, while a high RoCoF may trip the generating units unexpectedly.

To address these issues, various techniques are developed and reported in the literature [2]–[7]. One possible solution is to emulate the inertia and damping characteristic of a real synchronous machine, which is achieved by implementing virtual synchronous machine control for power converters. [2]–[3]. Although this technique proves to be effective in improving the frequency regulation performance, bulky and costly energy storage systems are required in the DC side to provide the real power support after a frequency event. Alternatively, a wind generation system with an interfacing converter can also have the similar effect [4]. In specific, the rotor speed can be adaptively regulated so as to improve the inertial response, whereas subsequent rotor speed recovery procedure may deteriorate the performance and can even lead to instability [5]. In addition, it is also revealed that the energy stored in DC-link capacitors can be explored to enhance the frequency regulation. The corresponding applications have already been reported in the grid-

connected DC/AC power converter [6]–[7] and modular multilevel converter (MMC) system [8]. As considerably large DC-link capacitors are needed to provide the surplus real power, such techniques may not be practical according to power converter design guidelines.

Most of the aforementioned techniques attempt to provide the frequency support from the power generation side. Yet, it is also possible to achieve the similar target through the demand side management. Recently, the electric spring (ES) concept is proposed and becomes a promising solution for the grid voltage and frequency control [9]. An ES is a converter connected in series with a noncritical load (NCL), such as water heaters and air conditioners. The voltage of a NCL is not crucial and can be varied in a reasonable range. Up till now, several types of ES have been developed. They are either based on DC capacitors [10]–[14] or powered by energy storage systems [15]–[17]. From a cost perspective, the ESs with DC capacitors are more preferable as there are no additional energy storage systems required. Among them, a typical implementation is reported in [15], which regulates the NCL voltage for primary frequency regulation. However, for the capacitor-based ES, its output voltage has to be regulated in quadrature with the NCL current. Therefore, the injected reactive power becomes coupled and uncontrollable. Similarly, the coupling effect between real and reactive powers also occurs in [16]. The essential reason behind this coupling effect is that a single ES can provide at most two control degree of freedoms, i.e., the AC voltage magnitude and phase angle. As the phase angle is restricted due to the storage energy limitation of the capacitor, it is impossible for the single ES to achieve multiple independent control targets simultaneously, i.e., the DC-link voltage control, real power control, and reactive power control. Although this issue is later solved by the ES with a novel back-to-back architecture [17], a low-frequency transformer is required for the isolation. The installation of transformer limits the power density of the electric spring, because it is usually heavy in weight and bulky in size.

In view of these technical limitations, a transformless ES with completely decoupled control of real and reactive power is proposed in this paper. The entire circuit contains a series voltage-controlled converter as well as a parallel current-controlled converter, both connecting with the NCL. The grid frequency support is performed by regulating the NCL voltage through the series-connected converter, while the DC-link voltage control as well as the reactive power control are achieved by regulating the current of the parallel-connected converter. To validate the feasibility of the proposed ES, real-time HIL results are provided.

Fig. 1. Circuit diagram of the proposed transformless electric spring.

II. CIRCUIT CONFIGURATION AND ANALYSIS

The circuit diagram of the proposed transformless ES is shown in Fig. 1. v_o and i_o are the voltage and current of the NCL; v_g and i_g are the grid voltage and current, respectively. Switches Q_1 and Q_2 form a half-bridge converter that is connected in series with the NCL. Its output voltage is denoted by v_{es} . Switches Q_3 and Q_4 form another converter, which is paralleled with the NCL. i_1 and i_2 are the currents of the series and parallel converter, respectively. v_{dc} is the DC-link capacitor voltage. In order to effectively attenuate high-frequency switching harmonics, filter inductors L_f and capacitor C_f are also employed in the circuit.

The ES frequency regulation principle is briefly explained as follows: Suppose that the grid frequency decreases from its nominal value, the series converter will operate accordingly to increase v_{es} and decrease v_o . As a result, the NCL will consume less real power, which subsequently restores the grid frequency value to some extent. Meanwhile, the parallel converter is responsible for the DC-link voltage and reactive power regulations. It should be mentioned that the operating principle is similar in case the grid frequency increases a little bit from its nominal value. In that case, the series converter will make the NCL to consume more real power.

A. Real Power Regulation.

According to the Kirchhoff's Voltage Law (KVL),

$$v_o + v_{es} = v_g \quad (1)$$

As the filter capacitor C_{f1} exhibits a considerably large impedance value at the fundamental frequency, it can be approximated that:

$$i_1(j\omega) \approx i_g(j\omega) \quad (2)$$

According to the Kirchhoff's Current Law (KCL) at node X,

$$i_1(j\omega) = i_2(j\omega) + i_o(j\omega) \quad (3)$$

A better illustration is provided by the ES phasor diagram shown in Fig. 2. For the convenience of statement, the axis that is in phase with v_g is defined as the d -axis, while the orthogonal axis is defined as the q -axis. In this paper, the NCL is considered to be a purely resistive load. However, it should be emphasized that the proposed ES and its control strategy are also valid for any complex N-CLs. The series converter operates as a voltage source and its output AC voltage v_{es} is intentionally regulated in phase with v_g

Fig. 2. Steady-state phasor diagrams of the transformless electric spring. (a). Suppressing mode as $v_o < v_g$. (b). Supporting mode as $v_o > v_g$.

$$v_{es} = (1 - m) \cdot v_g \quad (4)$$

where m is a ratio. Hence, the NCL voltage is expressed as

$$v_o = m \cdot v_g \quad (5)$$

Notice that the value of m should be kept within a certain range to comply with the NCL operation requirement [17]. When m is smaller than 1, the ES operate in the suppressing mode ($v_o < v_g$) and vice-versa. As the value of m directly determines the NCL real power consumption, it will be adaptively regulated based on the grid frequency. The NCL current i_o and real power are calculated as:

$$i_o = m \cdot \frac{v_g}{R_L}, \quad P_o = m^2 \cdot \frac{v_g^2}{R_L} \quad (6)$$

B. DC-link Voltage Regulation.

On the other hand, the current relationship is also clearly illustrated by the phasor triangle in Fig. 2, where the current i_2 is regulated by the current-controlled parallel converter. To maintain the DC-link voltage in the steady state, the real powers of series converter and parallel converter should be balanced:

$$i_{1d} \cdot v_{es} + i_{2d} \cdot v_o = 0 \quad (7)$$

This condition can be satisfied as long as the steady-state value of i_{2d} is regulated as

$$i_{2d} = \frac{v_{es}}{v_o} \cdot i_{1d} = (m^2 - m) \cdot \frac{v_g}{R_L} \quad (8)$$

Given that the DC-link voltage deviates from its reference value v_{dcref} , the DC voltage error can be readily eliminated by regulating the d -axis reference current i_{2dref} through a PI controller.

$$i_{2dref} = (k_{p1} + \frac{k_{i1}}{s}) \cdot (v_{dc} - v_{dcref}) \quad (9)$$

where k_{p1} and k_{i1} are PI controller gains. Fig. 3 illustrates the DC voltage regulation principle. The equilibrium condition in (7) is reflected in Fig. 3(a), where the DC-link voltage v_{dc} equals the reference value. With an external disturbance, v_{dc} will deviate from v_{dcref} and the regulation procedures are shown in Fig. 3(b) and Fig. 3(c). In Fig. 3(b), v_{dc} is larger than v_{dcref} . According to the PI controller, i_{2d} will increase so that the DC capacitors are discharged. This procedure will 1-

Fig. 3. Principle of the DC-link voltage control. (a). equilibrium point. (b). discharging mode. (c). charging mode.

Fig. 4. Principle of the reactive power control.

-ast until v_{dc} returns to v_{dcref} . The similar principle works for the condition if v_{dc} is smaller than v_{dcref} , which is illustrated in Fig. 3(c).

C. Reactive Power Regulation.

While the d -axis component of i_2 is regulated to maintain the DC-link voltage, the q -axis component of i_2 can also be utilized to control the ES power factor, or in order words, the reactive power. The reference current i_{2qref} is determined as:

$$i_{2qref} = (k_{p2} + \frac{k_{i2}}{s}) \cdot (Q_{ref} - Q) \quad (10)$$

where k_{p2} and k_{i2} are PI controller gains, Q_{ref} is the reference reactive power, i_{2qref} is the q -axis reference current. Fig. 4 shows the reactive power control principle. It is clear that by changing i_{2q} , the power factor of ES-based smart load, i.e., φ can be flexibly adjusted, and the reactive power can also be regulated as desired.

III. OVERALL CONTROL SCHEME

The theoretical analyses in the last section indicates that the proposed transformless ES can independently control the real power, reactive power, and DC-link voltage. The detailed ES control overall scheme is displayed in Fig. 5. The overall scheme contains a series-unit controller and a parallel-unit controller, which will be respectively introduced in this section.

A. Series-unit Control.

As discussed before, the series-unit control provides the grid frequency support by indirectly regulating the voltage v_o . In Fig. 5, a linear relationship between the ratio m and the grid frequency ω_g is established.

$$m = 1 + b \cdot (\omega_g - \omega_{g0}) \quad (11)$$

Fig. 5. Overall ES control scheme.

In (11), ω_g can be obtained by a frequency-lock loop [18]. ω_{g0} is the nominal grid frequency, and b is the proportional gain that determined as

$$b = \Delta m_{\max} / \Delta \omega_{g \max} \quad (12)$$

where $\Delta \omega_{g \max}$ and $\Delta m_{\max}$ are the maximum grid frequency deviation and the maximum ratio deviation, respectively. In addition to the frequency control loop, an inner-loop voltage controller $G_v(s)$ is also implemented to eliminate the voltage tracking error e_v . $G_v(s)$ is expressed as

$$G_v(s) = k_{pv} + \frac{k_{iv} \cdot s}{s^2 + \omega_g^2} \quad (13)$$

where k_{pv} and k_{iv} are the proportional gain and resonant gain, respectively.

B. Parallel-unit Control.

The parallel converter is controlled as a current source. Its reference current is synthesized by orthogonal components i_{dref} and i_{qref} . The magnitude of i_{dref} is adaptively regulated according to the DC-link voltage and the magnitude of i_{qref} is determined by the reactive power reference Q_{ref} . Note that the phase angles for d -axis and q -axis current references are provided by an orthogonal signal generator (OSG), which is based on a second-order generalized integrator (SOGI) [19]. It should be mentioned that the reactive power reference Q_{ref} can either be a fixed value or adaptively regulated based on the grid voltage magnitude V_g . In this paper, Q_{ref} is simply selected as zero so that the electric spring operates with a unity power factor. Similarly, another proportional-resonant controller is also implemented for $G_i(s)$ to eliminate the current tracking error e_i .

$$G_i(s) = k_{pi} + \frac{k_{ii} \cdot s}{s^2 + \omega_g^2} \quad (14)$$

where k_{iv} and k_{ii} are the proportional gain and resonant gain, respectively. In addition, a load voltage feedforward control is incorporated into the current control loop in order to avoid the inrush current during the start-up procedure.

C. System Modelling and Analysis.

To make sure that the proposed ES can properly deliver the power and maintain the DC-link voltage, a small-signal modelling is built for the electric spring system and shown in Fig. 6. The system parameters are listed in Table. I. To keep the analysis simple, the inner-loop voltage and current controllers, which have faster dynamics than the power controllers, are represented by first-order transfer functions. The corresponding time constants τ_1 and τ_2 can be obtained through the comparison results shown in Fig. 7.

Fig. 6. Small-signal modelling of the electric spring system.

Fig. 7. First-order approximations of the inner-loop controllers. (a). Voltage controller representation when $\tau_1 = 0.022s$. (b) Current controller representation when $\tau_2 = 0.041s$.

TABLE I.
SYSTEM AND CONTROL PARAMETERS

Parameters	Descriptions	Values
V_g	AC voltage magnitude	110 V
ω_{g0}	Nominal grid frequency (RMS)	60 Hz
V_{dc}	DC-input voltage	400 V
$C_{dc1,2}$	DC-link capacitors	940 μF
$X_{f1,2}$	Filter inductors	2 mH
C_f	Filter capacitor	15 μF
R_L	NCL resistance	20 Ω
f_{sw}	Switching frequency	20 kHz
k_{pv}, k_{pi}	Proportional gains in PR	0.1, 0.1
k_{iv}, k_{ii}	Resonant gains in PR	100, 50
k_{p1}	Proportional gain in PI	0.2
k_{i1}	Resonant gain in PI	5
b	Conversion ratio	0.15

The real power charged by the series converter can be calculated and perturbed as:

$$\Delta P_s = V_{es0} \cdot \Delta I_{1d} + I_{1d0} \cdot \Delta V_{es} \quad (15)$$

where V_{es0} and I_{1d0} are the steady-state voltage and current of the series converter. From Fig. 6,

$$\Delta P_s = \frac{R_L b V_g I_{1d0} - b V_g V_{es0}}{R_L (1 + s\tau_1)} \cdot \Delta \omega_g + V_{es0} \cdot \frac{G_{p1}(s)}{1 + s\tau_2} \cdot \Delta V_{dc} \quad (16)$$

Similarly, the real power of the parallel converter can be calculated and perturbed as:

$$\Delta P_p = V_{o0} \cdot \Delta I_{2d} + I_{2d0} \cdot \Delta V_o \quad (17)$$

where V_{o0} and I_{2d0} are the steady-state voltage and current of the parallel converter. From Fig. 6,

$$\Delta P_p = \frac{V_{o0} G_{p1}(s)}{1 + s\tau_2} \cdot \Delta V_{dc} - \frac{b V_g I_{2d0}}{1 + s\tau_1} \cdot \Delta \omega_g \quad (18)$$

According to the characteristic of the DC-link capacitors,

$$\Delta P_s + \Delta P_p = G_{dc}(s) \cdot \Delta V_{dc} = \frac{1}{C_{dc} V_{dc0} \cdot s} \cdot \Delta V_{dc} \quad (19)$$

Combining (16), (18), and (19), the closed-loop transfer function from $\Delta \omega_g$ to ΔV_{dc} is derived as:

Fig. 8. Dynamic responses of DC-link voltage after an external disturbance.

$$\frac{\Delta V_{dc}}{\Delta \omega_g} = \frac{\frac{b^2 V_g^2 - b V_g V_{es0}}{R_L (1 + s\tau_1)}}{G_{dc}(s) - \frac{V_g G_{p1}(s)}{1 + s\tau_2}} \quad (20)$$

Then, the system pole can be readily obtained from (20) as:

$$s = \frac{C_{dc} V_{dc0} V_g k_{i1} - 1}{\tau_2 - C_{dc} V_{dc0} V_g k_{p1}} \quad (21)$$

Most commonly, the numerator of (21) is positive. Hence, the proportional gain k_{p1} should satisfy the below condition in order to stabilize the system.

$$k_{p1} > \frac{\tau_2}{C_{dc} V_{dc0} V_g} \quad (22)$$

In the meanwhile, the integral gain k_{i1} can be properly adjusted to achieve the desired dynamic performance. Fig. 8 shows the DC-link voltage responses with $k_{p1} = 0.2$ and a varying k_{i1} . To effectively mitigate the DC-link voltage deviations caused by disturbances, such as a grid frequency derivation, k_{i1} is selected as 5 in this paper.

Fig. 9. Laboratory setup for the HIL simulation.

Fig. 10. Steady-state ES voltages when $\omega_g = \omega_{g0}$.

Fig. 11. Steady-state ES currents when $\omega_g = \omega_{g0}$.

IV. REAL-TIME HIL SIMULATION RESULTS

The proposed electric spring and its control strategy were verified by the real time hardware-in-loop simulation results. Fig. 9 shows the laboratory setup for the HIL simulation. The proposed ES was built in Typhoon HIL 602+, while the ADC and digital controls were processed by a dSPACE MicroLabBox.

Initially, the grid frequency equals the nominal value ($\omega_g = \omega_{g0}$) and the ES series converter outputs zero fundamental voltage. In this case, the NCL also has the nominal voltage ($v_o = v_g$), which is illustrated by the steady-state waveforms in Fig. 10, where v_{dc1} and v_{dc2} are the DC capacitor voltages. Moreover, the ES steady-state currents are also shown in Fig. 11. As the ES is controlled to operate with unity power factor, the output current i_g is thereby in phase with the grid voltage v_g and the NCL current i_o .

Next, a 0.2 Hz sudden grid frequency drop occurs at t and Fig. 12 shows the dynamic response of the ES-based smart load. It can be seen that the NCL voltage v_o and the injected current i_g decrease accordingly, but the DC-link voltage still remains the constant value. It is clearly seen that the ES-based smart load will consume less real power in order to restore the frequency deviation.

Fig. 12. Dynamic response after a sudden grid frequency drop.

Fig. 13. Steady-state ES voltages after the frequency deviation.

Fig. 14. Steady-state ES currents after the frequency deviation.

Moreover, Fig. 13 and Fig. 14 show the steady-state ES voltages and currents after the grid frequency deviation. The series converter makes v_o to be less than v_g , while the parallel converter still ensures that the ES operates with unity power factor.

V. CONCLUSIONS AND FUTURE WORKS

This paper proposes a novel transformless electric spring to support the grid frequency regulation. Unlike the existing ESs, the proposed ES does not require a bulky transformer for the isolation and can independently deliver the real and reactive power as desired. The ES working principle and the associated control scheme are elaborated in details. In order to validate the feasibility of the proposed ES, real time hardware-in-loop simulation results obtained from Typhoon 602+ are provided. Presently, the proposed control strategy leads to a frequency-dependent NCL power consumption and therefore contributes to the damping effect in frequency

regulation. Qualitative analyses will be conducted in future works to explore the inertia emulation capability of the electric spring.

ACKNOWLEDGEMENT

The authors would like to sincerely appreciate the kind support from Power Electronics Microgrids and Subsea Electrical Systems Consortium (PEMSES) in University of Houston.

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