ANN Based Active and Reactive Power Control for Applications of Single-Phase Electric Springs

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ABSTRACT

Aiming at effective power management in micro grids with high penetration of renewable energy sources (RESs), the paper proposes a simple power control for the so-called second-generation, single-phase electric springs (ES-2), that overcomes the shortcomings of the existing ES control methods. By the proposed control, the unpredictable power generated from RESs is divided into two parts, i.e. the one absorbed by the ES-2 that still varies and the other injected into the grid that turns to be controllable, by a simple and accurate signal manipulation that works both at steady-state and during RES transients. It is believed that such a control is suitable for the distributed power generation, especially at domestic homes. In the paper, the proposed control is supported by a theoretical background. Its effectiveness is at first validated by simulations and then by experiments. To this purpose, a typical RES application is considered, and an experimental setup is arranged, built up around an ES-2 implementing the proposed control. Testing of the setup is carried out in three steps and proves not only the smooth operation of the ES-2 itself, but also its capability in running the application properly. Therefore, the intelligent control approach using ANN concept is more accurate and faster than the fuzzy control and conventional PI control scheme even for complex dynamical system.

INTRODUCTION

Centralized control is adopted in the existing power system where power generation mainly depends on the load prediction. Nowadays, with the increasing portion of power generated from the renewable energy sources (RESs) and injected into the power system, stability issues become more and more severe due to the RES intermittency Flexible alternating current transmission systems are used to control voltage and/or power flow . However, most of them are suitable for high- or medium-voltage applications, and cannot be used for future low-voltage microgrids with high RES penetration, such as roof photovoltaic (PV) and small power-rating wind plants . To cope with this need, the electric spring (ES) technology has been proposed for future distributed microgrids to transfer the line voltage fluctuations to the so-called non-critical loads (NCLs) , i.e. to the loads that tolerate a large supply voltage range, so as to keep regulated the voltage across the so-called critical loads (CLs), i.e. the loads that tolerate a narrow supply voltage range. The transfer occurs through an automatic balance of the load demand with the power generation, performed by ES. The set made of ES and NCLs forms the so-called smart load (SL).

. In present days, small distributed power stations are built closer to the intermitted renewable energy sources of low ratings which can supply power to solar houses, hybrid cars etc., by providing efficient power to the loads. A spring is a rigid object which repels based on their applications, that works on the principle of HOOKE’s law [2]. Spring is made of high yield strength elastic material to restore energy. Electric spring is analogues to the mechanical spring. Generally a spring can be used as a storage device, for reducing the effect of shocks and vibrations, pollution free, easy maintenance. In daily life, applications of spring are pogo stick, trampoline, and spring mattresses. Electric spring helps to provide continuous voltage for non-critical loads such as house-hold appliances. Whenever there is more generation of power through renewable sources, battery banks, super capacitors [3] are introduced to store power. The life time of these storage devices are low, and the cost of the battery is directly proportional to the capacity of the battery. Though they are unable to balance voltage supply and decomposition of batteries causes environmental problems. In such a case electric spring are introduced and can be used as energy storage devices. By connecting renewable energy sources along with electric spring to the grid [4], frequency, voltage stability can be maintained easily. It allows power demand based on its power generation. When connecting these renewable energy sources to grid, these energy sources do not have interruption of power supply so there will be voltage stability in grid. For any ac system especially for house hold appliances and industrial loads power factor is required, for house hold appliances power factor close to unity is required in order to reduce losses in the transmission lines and thereby reducing the cost of electricity bills also. For industrial loads power factor is required to improve the efficiency of equipments. For improving power factor various power factor correction methods such as passive capacitors, shunt condensers are used. For improving of power factor through electric spring various methods has been introduced such as by using PWM techniques, phase locked loops using the properties of d-q transformation but it does not make power factor close to unity, system makes complex and time consuming. When electric spring is implemented with ANN makes the power factor of the system close to unity. In general, the advantage of making power factor close to unity in ac systems is to ease the losses, improve the effectiveness of the system and improve the life of the equipments etc.

This solution, however, is unable to keep unaltered the grid voltage as it is regulated in an open-loop mode. Even if a closed-loop with a proportional integral (PI) regulator is added to regulate the grid voltage, it mainly takes care of the power factor correction rather than of the voltage regulation. In the δ control is proposed to adjust the instantaneous phase of CL voltage but relies on system modeling that utilizes the circuitry parameters. Recently, the radial-chordal decomposition (RCD) control is proposed in to decouple the control of the power angle of SL from the voltage across CL, which makes ES-2 ready to be embedded in many devices such as water heaters. However, it still has some shortcomings. For instance, the power angle of NCL should be known in advance, which prevents the use of the RCD control when NCL varies or is non-linear. Besides, it is difficult to obtain pure reactive power compensation by means of ES. Power control of ES-2 is studied in this paper with reference to a practical application. Let us consider a low power outdoor wind power plant as an example The maximum power point tracking (MPPT) technique is normally adopted in the wind and/or solar power generation plants . The tracked active power is consumed by the electrical loads at domestic homes, which are of both CL and NCL types.

Even if one can demonstrate that the RCD control can deal with such a situation, calculations necessary to determine the reactive power that ES must provide are very involved, especially during the transients. Aiming at the massive applications of ES-2 in the distributed power systems, this paper proposes a simple active and reactive power control as a solution to the shortcomings of the existing control methods. The proposed control not only decouples the active and reactive powers, but also relies on a local signal manipulation that does not need any information on the ES-2 circuitry parameters and the line voltage and parameters.

Electrical springs

Electric spring (ES) was first introduced in 2012 as a new smart grid technology to balance the power between the power supply and demand automatically . Therefore, power mismatch between the generation side and the demand side can be effectively alleviated. So far, a significant amount of research work has been conducted and rich research results have been achieved, which mainly consist of basic analyses, topological structures, and control strategies of ESs. The most basic function of ESs to keep active and reactive power balance for mitigating voltage and frequency fluctuation is described . Dynamic modeling for ESs to implement large-scale simulation research and a general analysis on the steady-state behavior of ESs , respectively.

Basic Principles of Electric Spring

The topology of ES-2 and the associated circuitry are drawn in Fig.1. In this figure, ES-2 is enclosed by the dashed line and consists of a single-phase voltage source inverter (VSI), an L filter and a capacitor whose voltage sums up to that of the NCL. Moreover, Z2 is the CL, Z3 is the NCL, vG represents the line voltage of the power system with RESs, R1 and L1 are the line resistance and inductance, respectively. The branch including vG and the line impedance supplies CL and SL. vSdenotes the voltage of point of common coupling (PCC), which is also the CL voltage.

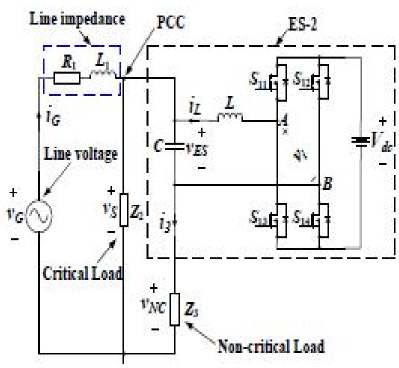


Fig. 1 Topology of ES-2 and associated circuitry.

electric loads are divided into two types, namely CLs and NCLs. ES is an electrical device that is able to regulate the CL voltage at a pre-set value while passing the voltage (and power) fluctuations from the sources to NCL.

A. Power Control of Existing ES-2 δ control

δ control is one of the power control methods for ES-2; its diagram is drawn in Fig. 2(a) and includes a double loop control. The outer loop is closed around the CL voltage by means of a PR regulator whilst the inner one is closed around the ES current by means of a P regulator. The purpose of δ control is to set the instantaneous phase of the reference voltage for the PR regulator. The process of δ calculation is based on a vector analysis and ensures that ES operates at constant input active power mode [14]. Once the CL voltage is regulated, the control objectives of ES-2 are achieved. The δ calculation, which is executed by the blocks enclosed by the dashed line of Fig. 2(a), is the key element that affects operation of ES-2 and, hence, the fulfillment of the control objectives directly. However, δ calculation is based on a model of the ES-2 topology, shown in Fig. 1, and utilizes the parameters of the circuitry, thus impairing the control accuracy as they vary. What's more, as δ control is a phase control based on a vector diagram, it requires the RMS value of vG (marked as VG) to calculate the angle δ.

B. Power Control of Existing ES-2 RCD control

Consequently, VG should be known in advance. In order to detect VG, communication technique is needed between two neighboring ESs because vG is far away from ES-2 due to the transmission line between the ES-2 and the grid. This drawback leads to cost up when applying δ control to ES-2. The RCD control diagram for ES-2 is drawn in Fig. 2(b). The ES voltage is here decomposed into two directions, named the radial and chordal ones. The PCC voltage is regulated by adjusting the apparent power absorbed by SL using the radial control whilst the power angle of SL is regulated at the pre-set value by the chordal control. This feature makes the SL smart as it allows ES-2 to achieve independent control of the apparent power and the power angle of SL. From this perspective, it follows that the RCD control aims at the power control of SL.

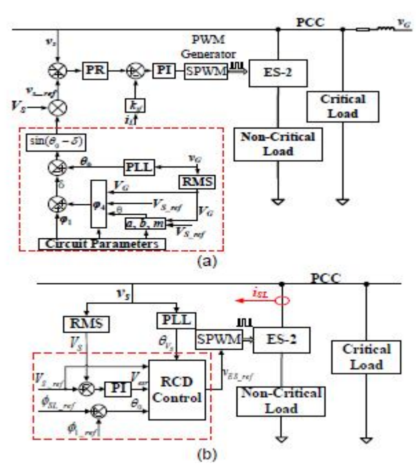


Fig. 2 ES-2 control diagrams for (a) δ control, (b) RCD control.

Requirements for the Proposed Power Control Further to the analysis above, it would be desirable to dispose of a new power control method with the following requirements:

 No need to detect the information of grid voltage which is a far away from PCC, like δ control

 Need to decouple the control loop of the input active power from that of the PCC voltage or of the input reactive power

 Easy to implement and less computational burden compared to other techniques

For an ES installed at the same location as the wind power plant, the active and reactive powers generated by the plant can be measured by ES even if they are changing quickly. As a result, ES in such situation can carry out the control of both the input active and reactive power and, by the latter control, can regulate the RMS value of the CL voltage at the pre-set value. For instance, the control scheme in cannot handle the active power independently of the reactive one. Although constant active power compensation can be achieved by the δ control in , its shortcomings cannot still be overcome. Instead, the RCD control in can regulate the grid voltage and can also correct the power factor of SL by the independent radial and chordal actions. However, does not discuss the situation in which the input active power is constant.

Power Control of ES-2

The control diagram of the proposed simple power control is shown in the block of Fig. 3(a) enclosed by the dashed line. The control calls for the detection of variables such as the input current i1 and the CL voltage vS. The input active and reactive powers of the ES system, marked as Pin and Qin, are obtained by manipulating the instantaneous values of vS and i1 as illustrated by the scheme of Fig. 3(b), of which the function block already exists in the Matlab/Simulink. According to Fig. 3(a), the RMS value and the instantaneous phase of the CL voltage are detected by the RMS and PLL blocks, respectively. The powers Pin and Qin are controlled by separate PI regulators.

Specifically, the regulator in the d-axis controls Pin and that one in the q-axis controls Qin. Alternatively, if the control objective is the CL voltage instead of Qin, a loop outer the q-axis is added closed with a PI regulator, and its output represents the reference for Qin, designated as Qinref. The output signals of the PI regulators in both the loops are processed through the inverse dq-to-αβ transformation to get the modulation signal vcomp1. It should be noticed that functionality of harmonic suppression is added in Fig. 3(a) by subtracting the harmonic component denoted as vS_h from vcomp1. The drive signals for the VSI transistors are obtained by the SPWM technique, just after a limiter

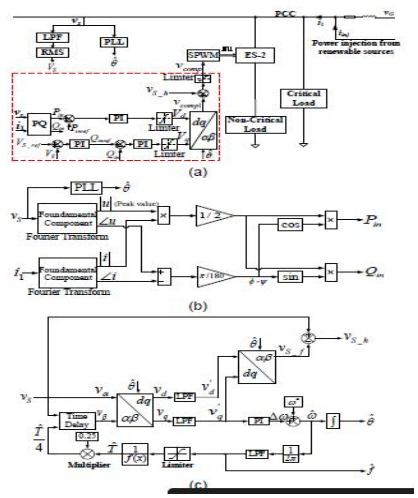


Fig. 3 The proposed power control of ES-2. a) Control diagram. (b) Calculation diagram of active and reactive power. (c) Functions of PLL and harmonic extraction.

Single-Phase PLL

The traditional Synchronous Reference Frame PLL (SRF-PLL) [20] is utilized to estimate the phase θ and the angular frequency ω of vS. The diagram of the SRF-PLL is detailed in Fig. 3(c), where the estimated values of θ and ω are marked asθˆ andωˆ, respectively. And ω* denotes 100π.

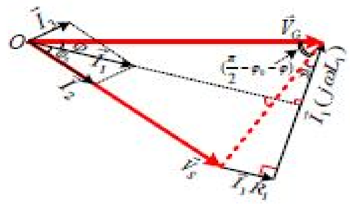


Fig. 4 Vector diagram of ES-2 circuit with resistive CL.

To simplify the analysis, both CL and NCL are chosen of resistive types. It should be noticed that they can be any other linear types. For the ES-2 system under simulation, the control objectives are formulated as follows:

RMS value of the PCC voltage or input reactive power is regulated at a pre-set values, and

input active power Pin tracks the pre-set value Pinref.

Three situations are investigated, namely

- Pinref varies at fixed VG
- VG varies at fixed Pinref
- Distorted VG

Artificial neural network (ANN)

A feed-forward network is adopted here as this architecture is reported to be suitable for problems based on pattern identification. A network first needs to be trained before interpreting new information. Several different algorithms are available for training of neural networks, but the back-propagation algorithm is the most versatile and robust technique for it provides the most efficient learning procedure for multilayer neural networks. Also, the fact that back-propagation algorithms are especially capable to solve problems of prediction makes them highly popular During training of the network, data are processed through the network until they reach the output layer (forward pass). In this layer, the output is compared to the measured values (the \true" output). The difference or error between the two is processed back through the network (backward pass) updating the individual weights of the connections and the biases of the individual neurons. The input and output data are mostly represented as vectors called training pairs. The process as mentioned above is repeated for all the training pairs in the data set, until the network error has converged to a threshold minimum defined by a corresponding cost function, usually the root mean squared error (RMSE).

SIMULINK MODEL OF PROPOSED SYSTEM

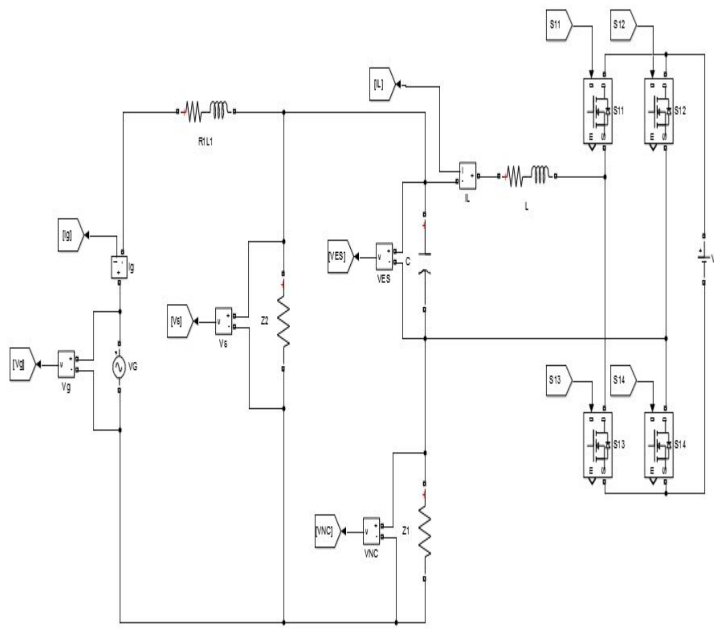
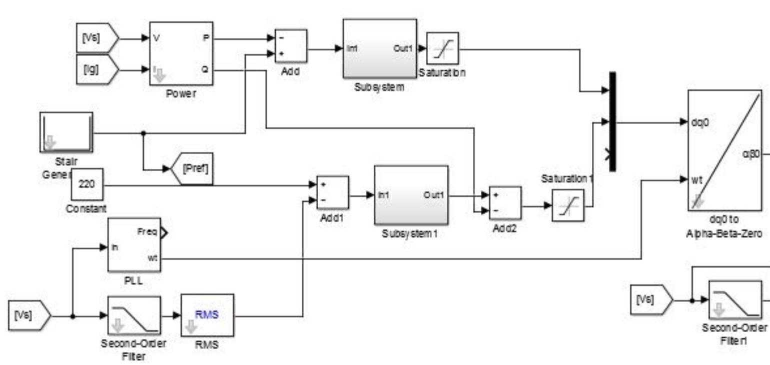


Fig:5 simulink model of proposed system



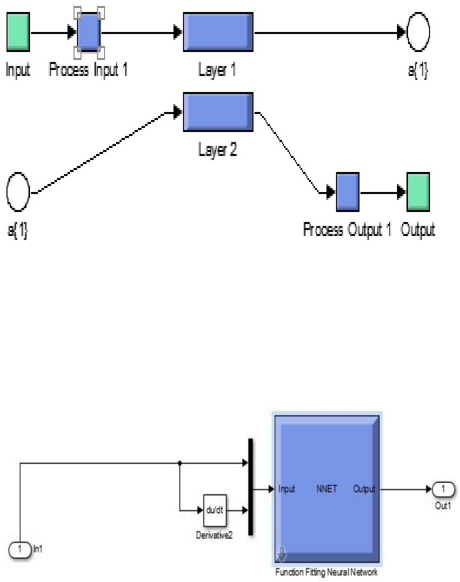
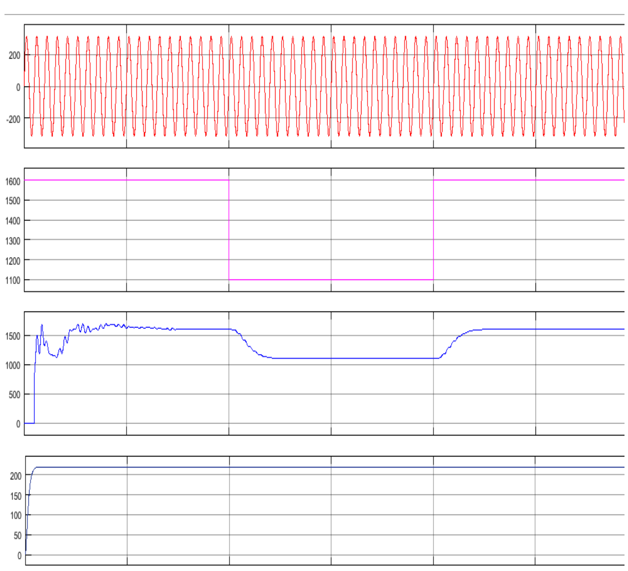
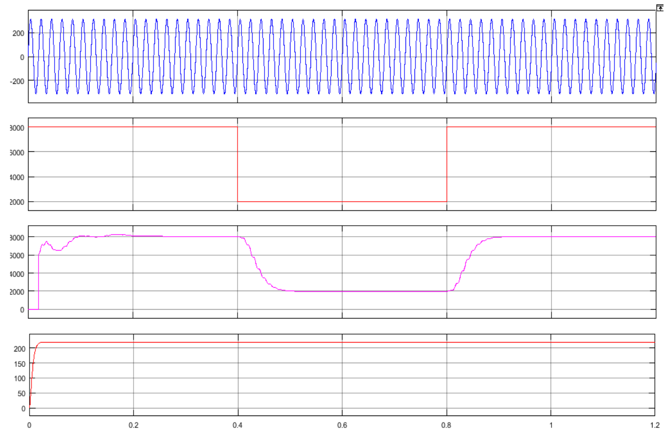
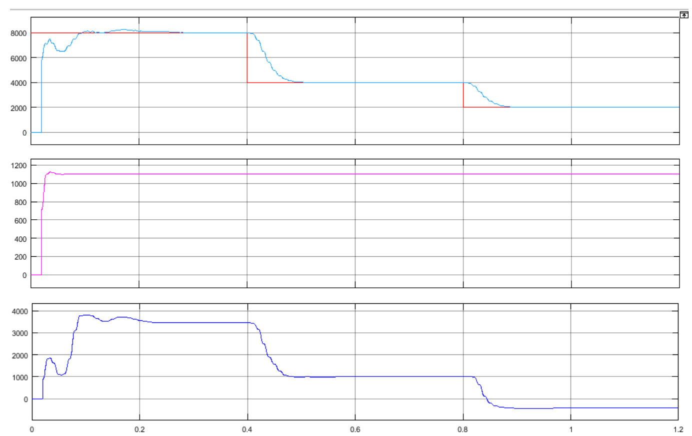


Fig:6 Block diagram for ANN







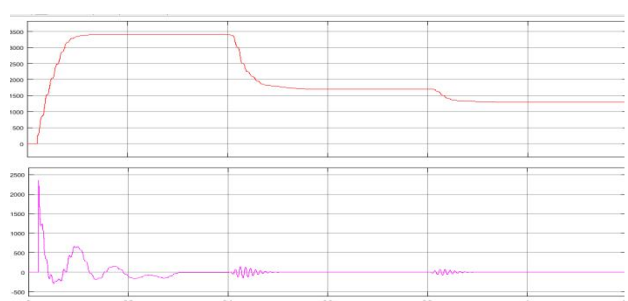


Fig. 7 Simulation waveforms under different variations of the input active power. (a) From 1.6kW to 1.1kW and then back to 1.6kW @ *VG*=230V. (b) From 8kW to 2kW and then back to 8kW @ *VG*=200V. (c) From 8kW to 4kW and then to 2kW @ *VG*=200V.

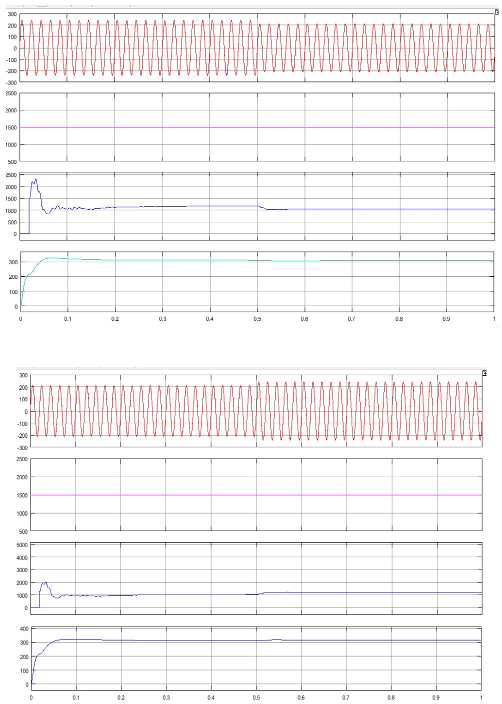
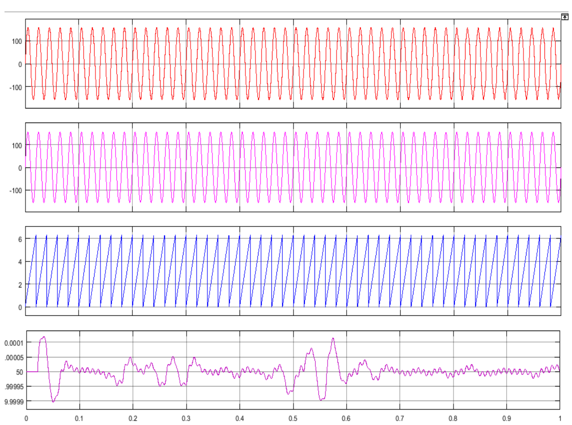


Fig. 8 Transient ES-2 responses to a change of the line voltage with *Pinref*=1.5kW. (a) From 240V to 210V. (b) From 210V to 240V.



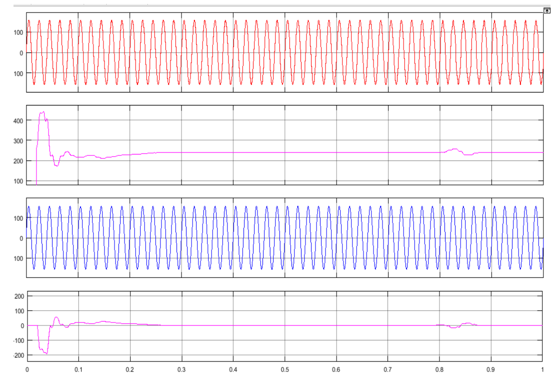


Fig. 9 Simulation waveforms before and after grid distortion. (a) Results of PLL. (b) Results of active and reactive power of ES system

CONCLUSION

The input active and reactive power control is proposed for the purpose of practical application of ES-2 in this paper. An overall review and analysis have been done on the existing control strategies such as δ control and RCD control, revealing that the essences of the controls on ES-2 are to control the input active power and reactive power. If being equipped together with the distributed generation from RESs, the ES-2 can manage the fluctuated power and make sure the controllable power to grid, which means that the ES-2 is able to deal with the active power captured by MPPT algorithm. Simulations have been done on the steady and transient analysis and also under the grid anomalies, validating the effectiveness of the proposed control. Three steps have been set in the experiments to verify the three typical situations and namely the active power generated by the GCC from RESs are, 1) more than; 2) less than; 3) the same as the load demand. Tested results have validated the proposed control. Intelligent control approach (ANN controller) with inclusion of slider gain provides better dynamic performance and reduces the oscillation of the frequency deviation and the active and reactive power is controlled

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