Performance optimization of a hybrid micro-grid based on double-loop MPPT and SVC-MERS

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Abstract. With ever-increasing concerns on environmental pollution and energy shortage, the development of renewable resource has attracted a lot of attention. This paper first reviews both the wind and photovoltaic (PV) generation techniques and approaches of micro-grid voltage control. Then, a novel islanded micro-grid, which consists of wind & PV generation and hybrid-energy storage device, is built for application to remote and isolated areas. For the PV power generation branch, a double-maximum power point tracking (MPPT) technique is developed to trace the sunlight and regulate the tilt angle of PV panels. For wind-power generation branch, squirrel cage induction generator (SCIG) is used as its simple structure, robustness and less cost. In order to stabilize the output voltage of SCIGs, a new Static Var Compensator named magnetic energy recovery switch (SVC-MERS) is applied. Finally, experimental results confirm that both of the proposed methods can improve the efficiency of PV power generation and voltage stability of the micro-grid, respectively.

1. Introduction

In the last thirty years, renewable energy resources have attracted wide attention due to fossil energy shortage and environment pollution. With the advantages of being abundant in nature and non-pollutant, both of wind and PV power are the most promising clean energy resource.

Many kinds of MPPTs, mainly include hill-climbing searching, incremental conductance, open-circuit voltage/short-circuit current [1] and some others [2], have already been proposed, too. These methods, by controlling the output voltage/current of DC-DC converter, cannot output the maximum power since sunlight’s radiation angle is changing all the time. In [3], a dual mechatronic MPPT controller and a dual-axis solar programmable logical controller have been designed to acquire higher intensity of sunlight by means of continuously adjusting the tilt angle of solar panels.

With regard to wind turbine generator, different kinds of electric machines have been developed, including induction machine, permanent magnet motor and switched reluctance machines [4]. Characteristics of the DFIG includes less weight, small volume and low cost whereas it needs to equip a multi-pole gearbox and slip rings [5]. For the great advantages of high reliability and nearly maintenance free, the PSMG is hence a trend and promised to expand as multi-megawatt generators in inaccessible locations such as offshore-wind farms [6].

Many kinds of control strategies, based on regulating the grid-connected inverters, have been presented in [7] such as droop control, voltage/frequency (V/f) control and constant active power/reactive power (P/Q) control. On the other hand, battery energy storage, super-capacitor energy storage and some other methods were studied in [8] to improve the performance of power stability.
Consequently, it needs an external device, such as thyristor switched capacitors (TSC) or thyristor controlled reactor (TCR) or static synchronous compensator (STATCOM) or SVC-MERS [9], to regulate the reactive power separately instead of via converters.

In section II, the structure of the proposed islanded micro-grid is presented. Afterward, a double-MPPT is developed in section III by tracking the maximum radiation angle of sunlight. In section IV, the proposed SVC-MERS is introduced in detail. In section V, a small scale experimental system is established and performance of system voltage stabilizing is verified by experimental results. Finally, conclusions and future trends are pointed out in Section VI.

2. The proposed island micro-grid
Figure.1 shows structure of the proposed micro-grid. Obviously, DGs’ power generation efficiency is as critical as power balance for improving the reliability of the island micro-grid. Based on MPPTs, the former can be realized by exporting maximum power of sunlight or wind. The latter seems more difficult to be achieved because it can be influenced by load fluctuation and weather change.

An array of 11kW SCIG output voltage, with a fixed capacitor excitation, has been measured when the output power is increasing. As we know, output voltage drops acutely in the process of load enlarged. In consideration of reactive power compensator, SVC-MERS is harnessed as a variable capacitor to trace the load variation and supply the SCIGs with capacitive reactive power continuously.

The advantages, have also presented in [10] as a SCIG voltage controller, include high robustness, low loss and cost. Drawbacks of the new device have also been mentioned in the current researches. For instance, the current harmonics becomes unacceptable alone with the output power ascending and voltage of dc-capacitor also keeps sharp growth at the same time. So the operating range is greatly restricted.

3. The novel PV double-MPPT
Power captured from sunshine is influenced by two factors: Sunlight received via solar panel and Photovoltaic conversion efficiency. To extract maximum power, the optimal output-voltage can be calculated with the typical control strategies introduced in [11].

The tilt angle regulation is realized via a mechanical system as shown in Figure.2. Detail process is described in Figure.3. In the inside-loop, control signal is updated continuously to regulate output voltage dynamically. Using the hill-climbing searching control, error of output power, \( \Delta P_{\text{error}} \) is translated to switch gate signal. If the output power \( P_{\text{max}} \) is less than the limit value \( P_{\text{smallest}} \) smallest, the system would be reset. Value of \( P_{\text{smallest}} \) nearly equals to zero.

![Figure 1. Configuration of the micro-grid.](image-url)
4. Continuous reactive power compensator

Magnetic Energy Recovery Switch (MERS), is equivalent to a variable capacitor, has attracted widespread attention and application because of its simple configuration and phase control in line frequency.

4.1. Principle

As shown in Figure 4, a single phase SVC-MERS is composed of four switches, a small DC-capacitor and a reactor. To avoid capacitance short circuit, not more than two switches can be opened at the same time. The waveforms, according to the switch state, are depicted on the right side of Figure 4.
The switches, named G1 and G3, are synchronously turned on when the phase of source voltage is \( \alpha \) rad. The opening G1 lasts for half a cycle, however, G3 is closed about double \( \alpha \) rad earlier than G1. From \( \alpha \) rad to \( \pi-\alpha \) rad, the small capacitor is charged and discharged in turn. During only G1 opening, the voltage of capacitor remains \( V_{C-min} \) and MERS is bypassed. The mathematic equation can be described as following:

\[
\begin{align*}
\text{Mode A:} & \quad \omega^2 L C \frac{d^2 u_{MERS}}{d\theta^2} + r_0 \omega C \frac{du_{MERS}}{d\theta} + u_{MERS} = V_1(\theta) \mp V_{C-min} \\
\text{Mode B:} & \quad \omega L \frac{di}{d\theta} + r_0 (i \mp I_{st}) = V_1(\theta)
\end{align*}
\]

Where \( V_1(\theta) \) is the source voltage and defined as \( V_m \cdot \sin(\theta) \), \( \theta \) or \( V_m \) means its phase and amplitude respectively. \( \omega \) is the angular frequency. \( r_0 \) is the line resistance and very small. \( I_{st} \), related to the control point in Figure 4, is the current of reactor before the next mode started.

\[
I_{Apm-1st} = m_1 \pi + m_2 (\alpha + 0.5 \sin 2\alpha) + m_3 \sin(\omega_x \alpha + \varphi_x) - m_4 V_{C-min} \sin \alpha
\]

Where \( m_1, m_2, m_3, m_4, \omega_x \) and \( \varphi_x \) are positive constants.

According to equation (3), the output reactive power is obtained as equation (4) shown.

\[
Q_{SV-MERS} = Q_0 + C_1 \alpha + C_2 \sin 2\alpha + C_3 \sin(\omega_x \alpha + \varphi_x) - C_4 V_{C-min} \sin \alpha
\]

Where \( C_1-4 \) are positive constants. \( Q_0 \) is the output reactive power when both of \( V_{C-min} \) and \( \alpha \) equal to zero. In a certain system, these constants are justified by simulation and experiment.

4.2. Characteristics

The characteristic of SVC-MERS, as a continuously variable reactive power compensator, has been demonstrated by simulation as shown in Figure 5.

From equation (4), continuously variable reactive power can be realized by changing \( V_{C-min} \) and \( \alpha \) respectively and shown in Figure 5. In Figure 5 (a), increasing \( \alpha \) obviously leads \( Q_{SV-MERS} \) rapidly increased but it gets opposite effect when \( V_{C-min} \) is ascending as shown in Figure 5 (b). The \( Q_0 \) and \( C_\alpha \) are constants if \( \alpha \) is a given value. It needs to be pointed out that, different combination of \( V_{C-min} \) and \( \alpha \) can provide the same \( Q_{SV-MERS} \) and it has been proved in Figure 5 (b).
5. Experiments
In order to verify the effect of voltage regulation, experimental platform including SVC-MERS device is developed in this section.

5.1. Established experimental system
In this grid, power generation units include SCIGs Simulated Wind Power and PV arrays as shown in the Table of Figure 6. Features of SVC-MERS and load are also given.

5.2. Control system design
To keep grid voltage stability, voltage amplitude and power factor (PF) have been monitored in real-time. Dynamic response needs to trace each little change of the micro-grid. If the response is not timely, grid voltage may be hard to support the load and cause unintended failure. In Figure 6, control program is displayed with an additional part which is named Over-voltage Detection.

![Figure 6. Control program.](image-url)
5.3. Experimental results

Waveforms checking for SVC-MERS have been finished as shown in Figure 7. It includes four points ($\alpha, V_{C_{\text{min}}}$) such as (90, 0V), (100, 15V), (200, 10V) and (230, 43V). Curves of capacitor voltage, $V_{C_{\text{ab}}}$, line current $I_{AM} - I_{CM}$ are consistent with the theoretical analysis.

When the experimental system is stable operation, the RMS value of grid voltage can be stabilized at 400V as Figure 8 shown. However, some constraints must be considered such as current distortion and components’ ability to withstand voltage in practical application. Figure 9 shows the current THD of the proposed device and Figure 10 shows peak voltage of the small capacitor. When reactive power changes from $1.8Q_0$ to $2.8Q_0$ the measured THD is not exceeding the limiting value 5%. In the meanwhile, peak voltage of MERS capacitor is less than 1000V. The simulation results, which are mapped out on Figure 9 and Figure 10, are less than the experimental results because the simulation grid voltage is 380V rather than 400V.

![Waveform Checking](image1)

**Figure 7.** Experiment of control parameters optimization.

![RMS Voltage vs Load](image2)

**Figure 8.** Continuous reactive power compensation.

![THD vs Reactive Power](image3)

**Figure 9.** Current THD of the proposed device.
Figure 10. Peak voltage of dc-capacitor.

6. Conclusions and future work
For a hybrid micro-grid, solar power generation efficiency and voltage stability have been studied in this work. Double-loop PV MPPT and SVC-MERS techniques have been applied to improve power distribution reliability of the proposed system. Experimental results, consistent with theoretical analysis, support the performance improvement by using these techniques. In future research, power capacity of SVC-MERS needs to be considered and improved when it is applied to common power grid.

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