Research on three-phase VSR segmented PI synergetic control strategy based on LCL filter

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Abstract
In view of the resonance phenomenon caused by LCL filter introduced by voltage pulse width modulation (PWM) rectifier as well as the inability of traditional PI adjustment to meet the needs of different load changes, this article proposed a segmented PI synergetic control strategy for the LCL filter rectifier based on the proportional-integral manifold form synergetic control strategy. First of all, a synergetic controller based on the proportional-integral manifold was constructed; secondly, particle swarm optimization was used to optimize PI parameters under different load conditions; thirdly, the optimized PI parameters were used to establish a segmented trigger database, taking load impedance as the trigger condition. The control strategy made full use of the LCL filter's ability to suppress higher harmonics and the PI adjustment is simple and fast under specific loads. The synergetic control theory has a lot of advantages, including chatter-free, simple control ideas, easy implementation, etc. Simulation experiments verified that the control strategy could effectively reduce the harmonic content, avoid resonance phenomena and improve system stability, and it was characterized by high control accuracy and simple structure.

1 | INTRODUCTION

Due to good high-order harmonic suppression effect, LCL filters have been widely used in PWM voltage source rectifier (VSR) [1, 2] to solve the harmonic content problem of the VSR in the L filter. However, the introduction of the filter capacitor increases the resonance phenomenon. If it cannot be effectively removed, it will cause an increase in total harmonic distortion (THD) and damage to the system stability. Therefore, open-loop and closed-loop system with different LCL filter parameters at the same time have different resonance frequencies [3]. In order to avoid resonance problems, many control theories such as sliding mode control theory [4], virtual resistance method [5] as well as undamped control strategy [6] are applied to LCL-filtered VSR (LCL-VSR) [7]. In order to improve the reliability and design convenience of a grid-connected inverter system, a distributed control strategy for LCL inverters with input series and output parallel was proposed. This strategy can realize multiple control objectives of the grid-connected system, including suppression of resonance spikes and high power factor of the grid current [8]. Then a state feedback control method with active damping characteristics was proposed to solve the problem of unstable LCL inverter operation caused by grid-side impedance fluctuations and digital control delays. Based on the digital delay, a discrete state-space system model was established, and the state feedback feature analysis and design improved the stability and parameter adaptability of the system to a certain extent [9]. Aiming at the problems of the LCL inverter’s control capability degradation caused by the local inductive load at the end of the power generation weak grid, the damping resonance suppression and power adjustment method was proposed, and it consists of grid-connected current feedback robust control, quasi-proportional integral control as well as power adjustment.
1.1 | Motivation

In order to solve the resonance phenomenon, this article attempted to apply synergetic control theory (SCT) to LCL-VSR.

SCT uses the nonlinear characteristics of the system itself and the principle of directional self-organization, and a manifold was constructed in the state space of the controlled system, and then the system was reduced in order by a suitable manifold. The effect was similar to that of sliding-mode control, but there was no chattering problem, ensuring the system’s steady state and dynamic properties [10, 11]. First of all, SCT for nonlinear dissipative systems meet certain transient characteristics of closed-loop systems; second and ensure that the system maintains progressive stability on and near the attractor [12]. As a constraint variable of the system state space, a manifold is equivalent to the role of an attractor, and its formation reflects the direct self-organization process. Compared with the traditional control theory, the goal of the closed-loop system of SCT is changed. It is not necessary to linearize the system, and directly use the nonlinear characteristics of the system to create a new feedback method [13, 14, 15]. A synchronous generator excitation control system was designed based on SCT, with digital signal processing as the core controller, and it could take into account both the terminal voltage adjustment and the stable control of the rotor angular velocity and active power. Meanwhile, it has a strong robustness and can well suppress system oscillation [16]. By analysing the working mechanism of a permanent magnet synchronous motor wind power generation, a mathematical model based on fractional-order and grid voltage-oriented SCT was constructed, and a grid-connected wind power generation scheme based on fractional-order PI steering SCT was designed to meet the power factor and stability control CLAIM [17]. Later, a multi-interceptor control algorithm based on distributed SCT which has faster convergence speed and stable convergence process was constructed, and at the same time, it also has a strong robustness to external interference, so it improves the control efficiency of the multi-interceptor synergetic control system.

As an excellent control strategy [18], synergetic control strategy can well meet the controller design needs of LCL-VSR. The controller based on SCT is characterized by simpler structure, fewer control parameters as well as easy to implementation. It is suitable for the nonlinear system control, and is of great significance to study and solve modern complex and comprehensive system control problems.

1.2 | Contribution and article organization

According to the new strategy, the control strategy of three-phase grid-connected L.C.L. inverters without phase-locked loop, the current reference could be generated using the instantaneous power control scheme and the proposed positive-sequence voltage detector [19]. In contrast, this article also used the LCL filter to reduce the harmonic content of the VSR. At the same time, the SCT was used to build a controller to remove the resonance phenomenon, and the particle swarm optimization (PSO) was used to optimize parameters. Generally, the following points are the three main contributions achieved in this article:

1. Based on LCL-VSR, a new active damping control strategy was proposed, reducing the harmonic content and solving the emergence of resonance phenomenon.
2. Constructed a controller based on SCT in the form of proportional-integral manifold.
3. PSO was used to optimize PI parameters under different load conditions offline and the optimized PI parameters were adopted to build a segmented trigger database. Therefore, the deficiency of traditional PI that cannot achieve a better regulation of different load changes was solved.

The organization of this article is as follows. In Section 2, the LCL-VSR synergetic controller is designed and its convergence is analysed. In Section 3, the PSO is used to optimize offline to construct a segmented PI adjustment database. Finally, in Section 4 the effectiveness of the control strategy is verified by simulation experiments.

2 | LCL-VSR SWITCH FUNCTION MODEL

The LCL-VSR model is shown in Figure 1, where $e_{ag}$, $e_{gb}$, $e_{gc}$ are AC grid electromotive force with amplitude $U_m$, O is the neutral point; $L_g$ is the grid-side equivalent inductance; $u_{ac}$, $u_{dc}$, $u_{cc}$ is the capacitor voltage; $L$ is the rectifier-side equivalent inductance; the grid-side equivalent resistance $R_g$ is the sum of the inductance $L_g$, the filter capacitor $C_f$, and the equivalent resistance of the voltage source; the rectifier-side equivalent resistance $R$ is the sum of the inductance $L$ and the equivalent resistance of the switching device; the voltage and current at the input of the rectifier are $v_k$ and $i_k$, $k = a, b, c$; the output voltage is $u_{dc}$; the resistance $R_L$ is the equivalent load; the DC capacitance is $C$. To build the model, the following assumptions are made: ① The power supply is symmetrical, and the physical characteristics of the filter inductor are the same; ② The switching tube is ideal. $s_a$, $s_b$, $s_c$ are switching functions of unipolar binary logic rectifiers. According to KVL and KCL, the mathematical model of the three-phase LCL-VSR in the three-phase abc coordinate system was set as follows:

$$
\begin{align*}
L_g \frac{di_k}{dt} &= e_k - u_{c_k} \\
C_f \frac{du_{c_k}}{dt} &= i_k - i_k \\
L \frac{di_k}{dt} &= u_{c_k} - u_{dc} \left( s_k - \frac{1}{3} \sum_{i=a,b,c} s_i \right), k = a, b, c \\
C \frac{du_{dc}}{dt} &= \sum_{k=a,b,c} i_k s_k - i_L
\end{align*}
$$
The mathematical model in the synchronized dq coordinate system can be obtained using the equivalent transformation as follows:

\[
\begin{align*}
&\frac{dL_e \frac{di_{dq}}{dt}}{di_{dq}} = e_{dq} - i_{dq}R_g - u_{cd} + \omega L_e \frac{di_{dq}}{dt} \quad \text{(1)} \\
&\frac{dL_s \frac{di_{dq}}{dt}}{di_{dq}} = e_{dq} - i_{dq}R_g - u_{cq} - \omega L_s \frac{di_{dq}}{dt} \quad \text{(2)} \\
&\frac{L_{di}}{di} = u_{cd} - i_{d}R + \omega L_{di} - s_{d}u_{dc} \quad \text{(3)} \\
&\frac{L_{di}}{di} = u_{cd} - i_{d}R - \omega L_{di} - s_{q}u_{dc} \quad \text{(4)} \\
&\frac{C_{f} \frac{du_{cd}}{dt}}{du_{cd}} = i_{dq} - i_{d} + \omega C_{f} u_{cq} \quad \text{(5)} \\
&\frac{C_{f} \frac{du_{cd}}{dt}}{du_{cd}} = i_{dq} - i_{q} - \omega C_{f} u_{cd} \quad \text{(6)} \\
&C_{f} \frac{du_{cd}}{dt} = i_{d} \delta_{d} + i_{q} \delta_{q} - u_{dc} \frac{d}{dt} \quad \text{(7)}
\end{align*}
\]

By the equations (3) and (4) in (2), we can obtain the following:

\[
\begin{align*}
&\frac{dx_{1}}{dt} = u_{cd} - i_{d}R + \omega L_{iq} - s_{d}u_{dc} \\
&\frac{dx_{2}}{dt} = u_{cq} - i_{q}R - \omega L_{iq} - s_{q}u_{dc}
\end{align*}
\]

where \(x_{1} = L_{id} \), \(x_{2} = L_{iq} \).

The following switch function model can be obtained by sorting (3):

\[
\begin{align*}
&s_{d} = \frac{u_{cd} - i_{d}R + \omega L_{iq} - \frac{dx_{1}}{dt}}{u_{dc}} \quad \text{(8)} \\
&s_{q} = \frac{u_{cq} - i_{q}R - \omega L_{iq} - \frac{dx_{2}}{dt}}{u_{dc}}
\end{align*}
\]

3 | VSR SYNERGETIC CONTROL STRATEGY

3.1 | Synergetic controller design method

The basic idea of synergetic controller design is to determine the manifold which describes the state variable relationship of the system and combine it with the state equation of the controlled system to solve the control law of the system. Therefore, the design of synergetic controller can be summarized in two steps: one is to define the manifold, and the other is to control synthesis.

For the LCL filtered rectifier system, the SCT was applied to solve the output quantities \(s_{d}\) and \(s_{q}\) of the second-order system, and the system state equation is expressed as follows:

\[
\begin{align*}
\dot{x}_{1} &= u_{cd} - i_{d}R + \omega L_{iq} - s_{d}u_{dc} \\
\dot{x}_{2} &= u_{cq} - i_{q}R - \omega L_{iq} - s_{q}u_{dc}
\end{align*}
\]

where \(u_{cd}, u_{cq}, i_{d}, i_{q}, \omega, L\) and \(u_{dc}\) are system operating data. To control the state variables \(x_{1}\) and \(x_{2}\) simultaneously, a suitable manifold needed to be found.

Before setting the manifold, the error \(\xi\) was defined, and it is the difference between the expected and actual values of \(x_{1}\) and \(x_{2}\), aiming to make the control accuracy higher and the control effect better.

\[
\begin{align*}
\dot{\xi}_{1} &= x_{1}^{*} - x_{1} \\
\dot{\xi}_{2} &= x_{2}^{*} - x_{2}
\end{align*}
\]

The manifold form used in this article is proportional-integral form:

\[
\begin{align*}
\psi_{1} &= k_{1}\xi_{1} + k_{2}\int \xi_{1} dt \\
\psi_{2} &= k_{3}\xi_{2} + k_{4}\int \xi_{2} dt
\end{align*}
\]

where \(k_{1}, k_{2}\) are proportional control parameters and \(k_{3}, k_{4}\) are integral control parameters.
\[ \psi = \xi \quad (8) \]

Compared with the traditional manifold form only containing error (8), the proportional integral form can take advantage of the rapid response of proportional control and the elimination of static error characteristics of integral control to improve response speed and reduce system error.

The dynamic evolution law of the synergetic control algorithm can be mathematically expressed by the first-order differential equation established by the set manifold and the dynamic convergence equation.

\[
\begin{align*}
T_1 \dot{\psi}_1 + \psi_1 &= 0 \\
T_2 \dot{\psi}_2 + \psi_2 &= 0
\end{align*}
\quad (9)
\]

where \( T_1 \) and \( T_2 \) are control parameters and are all greater than zero, representing the convergence speed of the manifold. Under the action of the switch functions \( s_d \) and \( s_q \), the synergetic controller made the system reach a stable equilibrium point along the manifold by controlling parameters \( T_1 \) and \( T_2 \), so that the system convergence changed from a random state to a stable state on or near the manifold.

### 3.2 Convergence analysis of synergetic control

An error analysis was performed on the LCL-VSR control system to solve the error. According to (7) and (9), the following equation can be obtained:

\[
\begin{align*}
T_1 k_1 \dot{\xi}_1 + (T_1 k_2 + k_1) \xi_1 + k_2 \int \xi_1 dt &= 0 \\
T_2 k_4 \dot{\xi}_2 + (T_2 k_4 + k_3) \xi_2 + k_4 \int \xi_2 dt &= 0
\end{align*}
\quad (10)
\]

After derivating both sides of Equation (10) simultaneously, the following equation can be obtained:

\[
\begin{align*}
T_1 k_1 \dot{\xi}_1 + (T_1 k_2 + k_1) \xi_1 + k_2 \xi_1 &= 0 \\
T_2 k_4 \dot{\xi}_2 + (T_2 k_4 + k_3) \xi_2 + k_4 \xi_2 &= 0
\end{align*}
\quad (11)
\]

Solve the eigenvalue of (11) according to the second-order derivative rule as follows:

\[
\begin{align*}
\lambda_1 &= -\frac{1}{T_1}, \lambda_2 = \frac{k_2}{k_1} \\
\lambda_3 &= -\frac{1}{T_2}, \lambda_4 = \frac{k_4}{k_3}
\end{align*}
\quad (12)
\]

The solution of the second order differential equation is shown as follows:

\[
\begin{align*}
\xi_1 &= K_1 e^{\lambda_1 t} + K_2 e^{\lambda_2 t} \\
\xi_2 &= K_3 e^{\lambda_3 t} + K_4 e^{\lambda_4 t}
\end{align*}
\quad (13)
\]

where \( K_1, K_2, K_3 \) and \( K_4 \) are constants. Obviously, the values of \( K_1, K_2, K_3 \) and \( K_4 \) didn’t affect the convergence of the error \( \xi \) to zero.

### 3.3 Controller design

According to (6) and (10), the following equation can be obtained:

\[
\begin{align*}
\dot{x}_1 &= \left( \frac{1}{T_1} + \frac{k_2}{k_1} \right) \xi_1 + \frac{k_2}{T_1 k_1} \int \xi_1 dt \\
\dot{x}_2 &= \left( \frac{1}{T_2} + \frac{k_4}{k_3} \right) \xi_2 + \frac{k_4}{T_2 k_3} \int \xi_2 dt
\end{align*}
\quad (14)
\]

Take the expected values \( i_d^* = I_m \) and \( i_q^* = 0 \) and substitute them into Equation (6), then the following equation can be obtained:

\[
\begin{align*}
\dot{\xi}_1 &= L i_m - L i_d \\
\dot{\xi}_2 &= -L \dot{i}_q
\end{align*}
\quad (15)
\]

Where \( I_m \) can be obtained by adjusting the difference between the desired output voltage \( u_{dc}^* \) and the actual output \( u_{dc} \) through PI.

By Equation (2), the following equation can be obtained:

\[
\begin{align*}
u_{cd} &= e_{gd} - R_g i_d \\
u_{cq} &= e_{gq} - R_g i_q
\end{align*}
\quad (16)
\]

According to (4), (14), (15) and (16), the following switching function can be obtained:

\[
\begin{align*}
s_d &= \frac{e_{gd} - i_d (R_g + R) + \omega L i_q - \left( \frac{1}{T_1} + \frac{k_2}{k_1} \right) L (I_m - i_d) - \frac{k_2}{T_1 k_1} \int L (I_m - i_d) dt}{u_{dc}} \\
s_q &= \frac{e_{gq} - i_q (R_g + R) - \omega L i_d + \left( \frac{1}{T_2} + \frac{k_4}{k_3} \right) L i_q + \frac{k_4}{T_2 k_3} \int L i_q dt}{u_{dc}}
\end{align*}
\quad (17)
\]
Based on the above solution process, the flowchart of the synergistic control method is as follows:

### 3.4 | Optimization of offline control parameters based on particle swarm optimization

$I_{dc}$ was obtained by $u_{dc} - u_{dc}$ adjusted by PI, and the PI control parameters $k_p$ and $k_i$ were fixed values. The control effect was better under certain load conditions, but the control effect was not good when the load changed. In order to ensure that the PI control parameters can meet the real-time needs, a segmented PI synergistic control strategy was proposed. The PI control parameters under different load conditions were obtained through an offline optimization algorithm and a parameter database was constructed. The load impedance value was calculated from the DC output side voltage and current data collected by the sensor, it was used as the triggering condition for the segmented optimization control, and the value in the appropriate range was selected.

There are many methods for offline optimization processes, including Ant Colony algorithm, Genetic algorithm, PSO and so on. PSO has a lot of advantages, such as simple structure, easy to use, high convergence rate as well as meeting the minimum storage requirements. Meanwhile, PSO relies less on the set of initial points, and its convergence algorithm has a good robustness, which has been highly valued by the academic community [20–22]. Therefore, in this paper, the control parameters were obtained by PSO offline optimization.

#### 3.4.1 | Basic particle swarm algorithm

The output performance indicator function [23] is set as follows:

$$F = \int_0^L |u_{dc} - u_{dc}| dt$$

When looking for two optimal values in a D-dimensional space and a population of $n$ particles, the particles update their speed and position according to the following formula.

$$V_{id}^{k+1} = \sigma V_{id}^k + c_1 r_1 (p_{best}^k - X_{id}^k) + c_2 r_2 (gbest^k - X_{id}^k)$$

$$X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1}$$

where $\sigma$ is the inertia weight; $d = 1, \ldots, D; i = 1, \ldots, n; k$ is the current number of iterations; $V_{id}$ is the velocity of the particle; $X_{id}$ is the position of the particle; $p_{best}^k$ is the individual optimal value; $gbest$ is the group optimal value.

#### 3.4.2 | Offline parameter optimization

The initialization particle $p$ optimized by the above PSO is a set of two-dimensional vectors including $k_p$ and $k_i$, and the output performance index is the fitness value. When the fitness value updated based on the rated load meets the set performance index, the optimization is terminated to obtain $gbest$. Where $\sigma$ is 0.6, $c_1$ and $c_2$ are both 2, the maximum number of iterations is 1500, the particle swarm size is 50, and the minimum fitness value is 0.001.

#### 3.4.3 | Segmented online optimization control

According to the calculated impedance, the parameters $k_p$ and $k_i$ in the segmented database are called for PI online adjustment. This process can be achieved by a C program as follows:

```c
if (R_L > =24.5 & R_L <= 25.5)
    sys=[kp; ki];
    ...
else if (R_L > =49.5 & R_L < =50.5)
    sys=[kp; ki];
    ...
else if (R_L > =99 & R_L < =101)
    sys=[kp; ki];
    ...
```

$X_{id}^k$ is the current particle position; $r_1, r_2$ are random numbers between $[0, 1]$; $c_1, c_2$ are non-negative constant acceleration factors; $p_{best}$ is the individual extreme value; $gbest$ is the group extreme value.
4.1 Simulation design

According to Equation (17), a system simulation model can be built using the power electronic components in Matlab-Simulink. The LCL-VSR segmented PI synergetic control system is shown in Figure 3. The main parameters of the simulation experiment are shown in Table 1. Among them, the control parameters $k_i$ and $T_i$ were also obtained by PSO at the rated load and used as fixed values. Rated load resistance $R_L=50 \ \Omega$, $R_L=25 \ \Omega$ at overload, $R_L=100 \ \Omega$ at light load.

4.2 Simulation experiment results and analysis

4.2.1 Harmonics and power factor analysis at rated load

The harmonics of the grid-side phase A current at the rated load are shown in Figure 4. Among them, the voltage-feedforward decoupling control of the V-filtered VSR, except that it does not contain the filter capacitor $C_L$, the total inductance is equal to the total inductance of the LCL-VSR, and other parameters have not been modified.

For adopting the proportional-integral manifold form, $x_i^+ - x_i$ in Equation (6) means that error feedback such as $i_d$ and $i_q$ are introduced, so Equation (7) is the introduction of proportional-integral error feedback. The adjustment of the control parameters $k_i$ and $T_i$ in Equation (17) not only reduces the harmonic content and effectively eliminates the resonance phenomenon, but also improves the stability. For example, THD will decrease as $k_i$ increases, but the output voltage will overshoot and so on.

As observed from Figure 4, the amplitude and THD of the synergetic control of the LCL-VSR are significantly reduced compared with the voltage feedforward decoupling control of the L filter, and the THD reduced from 5.94% to 2.05%, Compared with passivity-based control LCL-VSR, it has an improvement of 0.40%. At the same time, THD = 1.03% when $R_L=25 \ \Omega$, THD = 4.29% when $R_L=100 \ \Omega$. As shown in Figure 4(b), it can be observed that the higher harmonics (80th order) at the switching frequency can produce better filtering effects [24], and the purpose of using the LCL filter is...
well achieved. In the analysis of the 10th to 40th harmonic bands, no resonance frequency appeared, especially there was no resonance point at 1.77 kHz (35th harmonic) [25], indicating that the segmented PI synergetic control strategy of LCL-VSR had a good suppression effect on resonance. From the analysis of the harmonic content and resonance point above, it could be concluded that the synergetic control strategy of LCL-VSR had better harmonic suppression ability and could effectively remove the resonance phenomenon.

4.2.2 | Analysis of steady-state performance under different load conditions

In order to effectively verify the control accuracy and stability of the segmented PI synergetic control strategy, the steady-state performance analysis at rated load, overload and light load will be performed below:

- Figure 5 shows the simulation results under the condition of rated load $R_L = 50 \, \Omega$.
- Figure 6 shows the simulation results under the condition of rated load $R_L = 25 \, \Omega$.
- Figure 7 shows the simulation results under the condition of light load $R_L = 100 \, \Omega$.

In Figures 5–7, S-PI represents segmented PI synergetic control, PI represents traditional PI synergetic control, and ref represents expected value. It could be seen from the figure that the LCL-VSR control system based on the segmented PI synergetic control strategy had a good stability and high control accuracy under three conditions, including load, overload as well as light load. Specific data is shown in Table 2 below.
**FIGURE 5** Simulation results under $R_L=50 \, \Omega$

(a) DC side voltage $u_{dc}$, (b) DC side current $i_L$.

**FIGURE 6** Simulation results under $R_L=25 \, \Omega$

(a) DC side voltage $u_{dc}$, (b) DC side current $i_L$. 
4.2.3 | Analysis of transient performance under sudden load changes

The simulation results of the sudden change of overload are shown in Figure 8. The rated load suddenly changed to the overload state at 0.1 s, and then returned to the rated state at 0.2 s. The S-PI curve fluctuated significantly better than the PI curve when a mutation occurred. The maximum error of the S-PI voltage curve in Figure (a) is 10.0 V, and the error ratio is 1.67%. The maximum error of the S-PI current curve in Figure (b) is 0.22 A, and the error ratio is 1.83%.

4.2.4 | Power factor analysis at rated load

The power factor at the rated load in Figure 9(a) is 0.997, which achieved the purpose of high-power operation. In addition, the power factors at overload and light load are 0.996 and 0.999, respectively, so the high-power operation was further confirmed.

Through an analysis on steady state, transient as well as power factor, it could be seen that the LCL-VSR controller based on the segmented PI synergetic control strategy had a good convergence speed and control accuracy, and could achieve the rectifier's high power operation.

| Name                | Value  |
|---------------------|--------|
| Control method      | S-PI   |
| Steady state time (ms) | 15.4 15.4 15.8 216 15 265 |
| Maximum deviation of $\mu_{dc}$ (v) | 0 0 0 -73.5 0 50.3 |
| Deviation rate (%)  | 0 0 0 12.3 0 8.4 |

5 | CONCLUSION

Aiming at the resonance phenomenon caused by the introduction of LCL filters in PWM rectifiers, in this article, a segmented PI synergetic control strategy based on LCL-VSR was proposed. This strategy took full advantage of synergetic control and optimized offline parameters through PSO to build a segmented parameter database for online real-time adjustment. The LCL-VSR segmented PI synergetic control strategy was more effective than the existing research methods in suppressing resonance generation and realizing precise controller control and stable system operation. Finally, simulation experiments were carried out to verify the feasibility of the control strategy.
FIGURE 8 Simulation results under over load mutation (a) DC side voltage $u_{dc}$, (b) DC side current $i_L$.

FIGURE 9 The relationship between power factor and voltage and current phase at rated load. (a) LCL-VSR power factor at rated load, (b) phase and phase diagram of voltage and current of phase a of LCL-VSR.
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