Energy and Power Engineering, **2013, 5, 661-666**
doi:10.4236/epe.2013.54B128 Published Online July 2013 (http://www.scirp.org/journal/epe)

The Coupling of Voltage and Frequecncy Response in Splitting Island and Its Effects on Load-shedding Relays*

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Received February, 2013

ABSTRACT

The voltage and frequency dynamics interact with each other in the island after splitting. The current frequency response model without considering the voltage effect would bring remarkable errors when analyzing the frequency dynamic progress in the island with large-capacity active-power shortage. In this paper, coupling effects of voltage and frequency are studied to indicate that initial reactive-power deficit and load characteristics have strong effects on the coupling effects of the voltage and frequency. Moreover, control effects of currently used under frequency load-shedding relays (UFLS) and under voltage load-shedding relays (UVLS) which are installed and executed independently are examined to find that it would sometimes cause excessive or inadequate control without considering the coupling, suggesting that it is necessary to develop coordinate control methods for voltage and frequency problems.

Keywords: Frequency Response; Coupling Effects; Splitting Island; Coordination Control

1. Introduction

Frequency, voltage and angle stability are three main kinds of power system stability, respectively [1]. However, when compared with the other two kinds, frequency stability has drawn less attention [2]. Currently, power grids in China has stepped into the age called large power grids, high voltage and large units[3], the frequency instability risk for the whole grid has decreased, but the risk for the region grids has increased[4], especially with the growing amount of renewable energy. Once the region grids disconnected with the main one due to splitting accident, currently installed under frequency load-shedding device (UFLS) may fail to ensure the island frequency stability [5].

At present, the last line of defense ensuring frequency stability is UFLS, whose setting is commonly based on single-machine single-load frequency model, ignoring voltage effects on frequency, such as the system frequency response model (SFR) [6] and average system frequency model (ASF) [7]. In fact, there are obvious differences for voltage and frequency at different buses due to space-time distribution characteristics [8]. However, there have been few studies about voltage effect on frequency dynamic. Owing to load characteristics, the negative effect of load-shedding on frequency recovery was first reported in [9]. Considering load-voltage effects， less amount of load can be shed when UFLS performs [10]. Although some researchers have realized the value of coupling effects on frequency dynamic, the key factors affecting the interaction and the mechanism have not been analyzed carefully yet. Furthermore, few studies have been done on the effect of the coupling on the third line of defense for power system safety.

In this paper, we will analysis how the coupling affects the frequency dynamic based on simulations of the conventional system. Our results would help to find the key factors affecting the interaction. Then the effects of the coupling on the UVLS and UFLS performance are verified to indicate that it is necessary to develop the frequency and voltage combined control method.

2. Frequency Changing Characteristic in the Island

The frequency response is decided by the active-power balance dynamic on the generator as expressed in equations (1) - (4), which suggest that the load voltage can affect the system frequency response through changing the absorbed active-power of its own :

$$M_{eq}\frac{df_{coi}}{dt}=\sum_{i=1}^{N}P_{i,m}-\sum_{i=1}^{N}P_{i,e}=\Delta P_{total}. \quad (1)$$

$$\sum_{i=1}^{N}P_{i,e}=\sum_{j\in L}P_{j,l}+\sum_{k\in M}\Delta P_{k,l}\ . \quad (2)$$

*The work Project Supported by State Grid Corporation of China, Major Projects on Planning and Operation Control of Large Scale Grid(SGCC-MPLG030-2 012)

$$P_j = P_j(U_j, f_j, x_j, t) \quad (j \in \mathrm{L}). \tag{3}$$

$$\Delta P_k = g_k(\dot{U}_{k1}, \dot{U}_{k2}, y_k) \quad (k \in \mathrm{M}). \tag{4}$$

where f_{coi}, $P_{i,m}$ and $P_{i,e}$ are the system inertia center frequency, the mechanical and electromagnetic power of the ith generator. Land M donates the load and line collections. P expresses active-power equation for loads, in which x is the state variables. G expresses load loss equations.

The single-machine single-load frequency model implies that the frequency can be predicted only by the intial active-power shortage (ΔP_0). This kind of model agrees well with actual response data when ΔP_0 is relatively small. However, in some situations which may cause large-capacity active-power shortage, for example when the region grid is spitted from the main one, we find the conclusions obtained from the conventional model are quite different from the fact, sometimes even opposite to the truth.

3. Simulation and Mechanism Analysis

3.1. Simulation Situations Description

The EPRI 36-bus system is as shown in **Figure 1** in which the governors and voltage regulator are carefully considered, the load was modeled through a composite model consisting of constant impedance and induction motor considering rotor mechanical and electromagnetic transient. All the eight generators adopt 6^{th}–order model, including governor and voltage regulator. Simulations were conducted on power system analysis software (PSASP) developed by China Electric Power Research Institute (CEPRI), the integration step-size was 0.01 s, total simulation time was 20 s.

A group of Lines (marked with X) was chosen as splitting section which divided the whole system into two parts. Focus attention on the bottom right area with positive initial active-power deficit as shown in **Figure 2**.

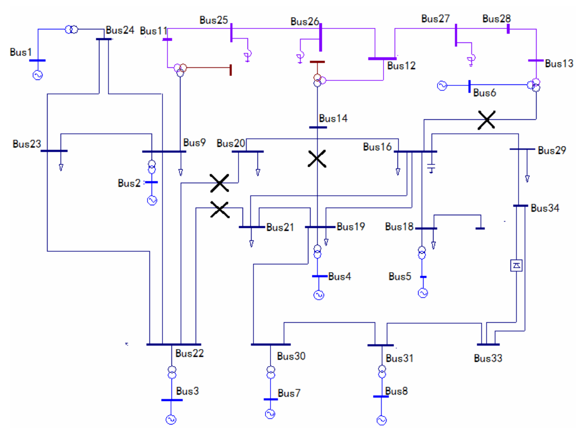

Figure 1. EPRI 36-bus system.

To simplify the fault situation, the splitting accident was simulated by disconnecting the section at 0.2 s.

Maintain the cross-section, effects of reactive-power transferred through the cross-section and load characteristics on the island frequency response were researched.

3.2. Effects of the Reactive-power Shortage

In conventional opinions, initial active-power shortage (ΔP_0) affects significantly the frequency response dynamic, but initial reactive-power shortage(ΔQ_0) slightly affects the frequency dynamic. However, after further research we find the change of ΔQ_0 has a remarkable effect on the frequency response through voltage and frequency coupling. Analyzing frequency without considering ΔQ_0 would bring obvious errors.

Maintain ΔP_0 at 6 p.u. (System base capacity is 100 MVA) , the change of ΔQ_0 is as shown in **Table 1.**

Figure 3 shows the voltage curves observed at Node 16.

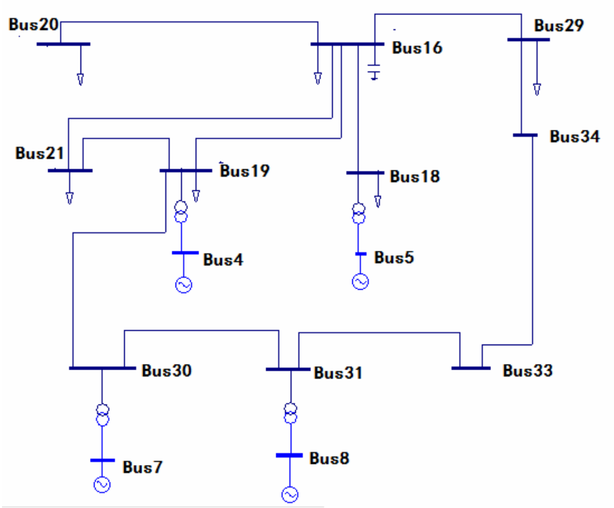

Figure 2. The sketch map for isolated island after splitting.

Table 1. Initial reactive-power shortage chang conditions.

Conditions	Power shortage conditions	
	Reactive-power shortage(p.u.)	Percentage in load reactive-power demand
1	0.5	8%
2	1	16%
3	1.25	20%
4	1.4	22.4%
5	1.5	24%
6	1.6	25.6%
7	2	32%
8	2.5	40%

It can be seen from **Figure 3** that the voltage decreases as ΔQ_0 increases, which can also be observed at other buses. From Equations (3) it can be noted that island voltage affects the total active-power absorbed by loads ($\sum P_L$). From Equations (2) it can be seen that $\sum P_L$ is the major part of the total electromagnetic active-power of the island($\sum P_e$). **Figure 4** shows the change of $\sum P_e$ with different ΔQ_0:

From **Figure 4** it can be observed that $\sum P_e$ decreases with ΔQ_0 increases. When the ΔQ_0 increases over a certain threshold, $\sum P_e$ drops sharply due to the voltage decline.

Meanwhile the change of total mechanical power in the island ($\sum P_m$) decided by governors at generators is as shown in **Figure 5**:

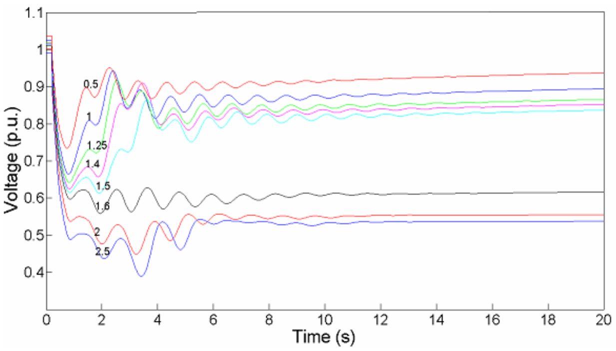

Figure 3. Voltage of Bus 16 under different ΔQ_0.

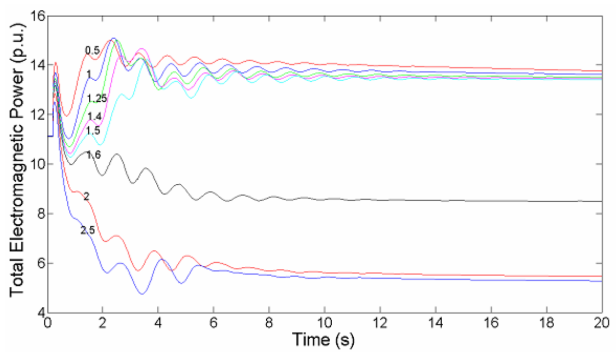

Figure 4. Values of total P_e under different ΔQ_0.

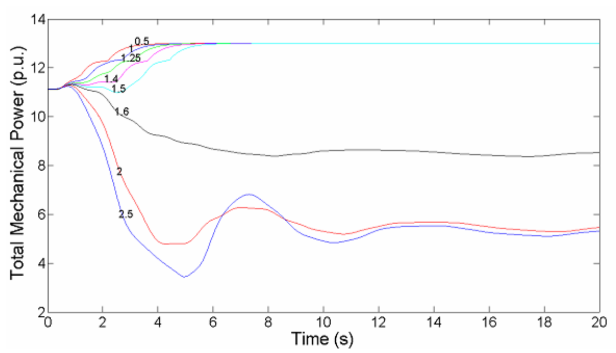

Figure 5. Total P_m under different ΔQ_0.

The difference between $\sum P_m$ shown in **Figure 5** and $\sum P_e$ shown in **Figure 4** ,which is called unbalanced active-power (ΔP_{total}) is shown in **Figure 6.**

From Equations (1) it can be seen that ΔP_{total} decides the frequency dynamic of the island, which is shown in **Figure 7**.

It can be seen from **Figure 7** that:

1) Under all conditions, frequency drops at the initial moment, the dropping rate of frequency decreases when ΔQ_0 increases, but the differences among all of the conditions are slight.

2) Effects of change of ΔQ_0 on frequency appears apparently after 0.4 s. When ΔQ_0 increases(See **Figure 3**) , voltage decreases ,leading to the decrease of $\sum P_L$ due to voltage effects on the load active-power. Then $\sum P_e$ decreases (See **Figure 4**), causing the increase of ΔP_{total} (See **Figure 6**). As a result, the frequency decided by ΔP_{total} increases when ΔQ_0 increases. If ΔQ_0 exceeds a certain threshold(e.g., 2 p.u.), causing voltage instability at some load buses, leading sharp drop of $\sum P_L$, whose decline value can be higher than ΔP_0, causing the sign of ΔP_{total} to change ,and then the frequency of the island would exceed rating value(*i.e.*, 50 Hz) despite of the severe ΔP_0.

From above discussions it can be implied that the frequency changing trend cannot be predicted accurately only byΔP_0. ΔQ_0 affects the voltage, changing frequency dynamic. Conclusions without considering ΔQ_0 can be far from, sometimes even inverse to the truth. It is necessary to consider reactive-power balance when analyzing island frequency.

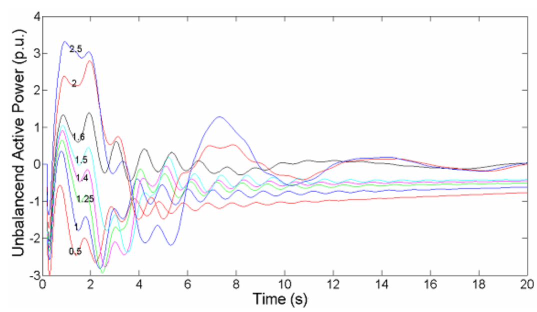

Figure 6. Unbalanced active-power under different ΔQ_0.

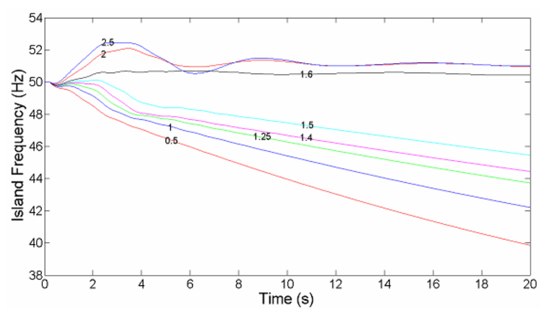

Figure 7. Frequency response under different ΔQ_0.

3.3. Effects of Load Characteristics

Maintain power transferred through the cross-section at 6+j1.5. The load characteristic was varied by changing the percentage of induction motor in the compositive load as shown in **Table 2**.

Figure 8 shows voltage of Bus 16:

It can be seen that the percentage of induction motor has a remarkable effect on voltage response. When the percentage increases, voltage decreases .When the percentage exceeds 30%, the motor instability happens due to voltage drop, whose active-power decreases sharply as well as the reactive-power clearly increases .The change of motor variables when the percentage is 40% is as shown in **Figure 9**.

In **Figure 9**, V,s,P and Q represent slip ratio, voltage, active-power, reactive-power of the motor, respectively.

The change of $\sum P_e$ is as shown in **Figure 10**:

It can be seen From **Figure 10** that $\sum P_e$ decreases with the percentage increases.

The frequency change curves in various situations are as shown in **Figure 11**:

ΔP_{total} is as shown in **Figure 12**:

It can be seen that the percentage of induction motor significantly affects the frequency dynamic through changing the island voltage. ΔP_{total} and frequency increase with the percentage increses. While the percentage exceeds a certain threshold, the sign of ΔP_{total} would change, causing that frequency of the island exceeds rating value despite of severe ΔP_0.

Table 2. Loda characteristic change in the island.

Model	Load model component	
	Induction motor(%)	Constant impedance(%)
1	0	100
2	20	80
3	25	75
4	30	70
5	35	65
6	40	60
7	45	55

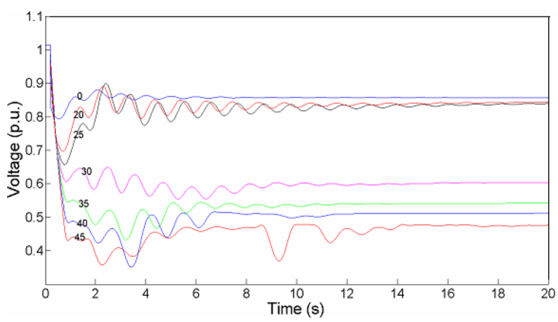

Figure 8. Voltage of Bus16 under different load characteristics.

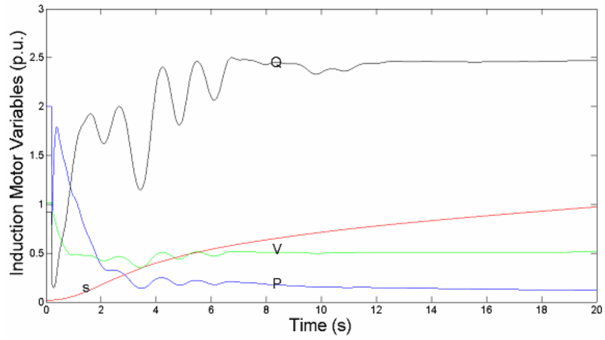

Figure 9. Related variables of the motor at Node 16 under different load characteristics.

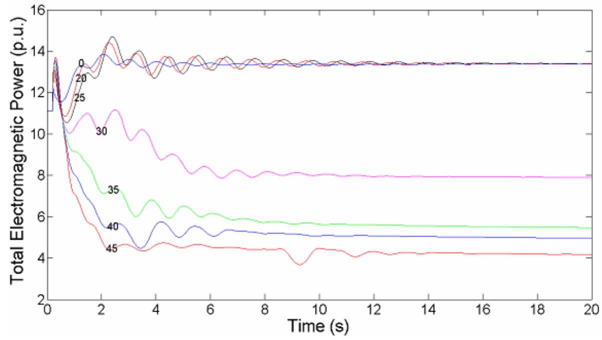

Figure 10. Response curves of total P_e in the isolated island under different load characteristics.

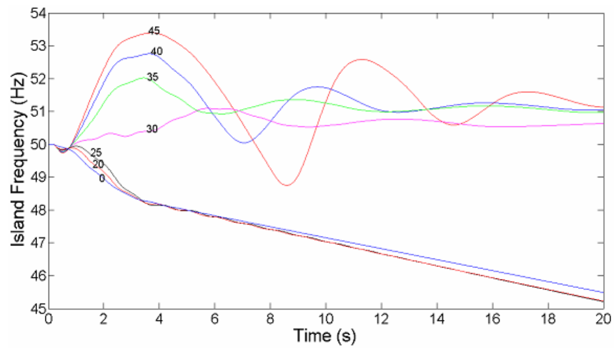

Figure 11. Response curves of frequency in the isolated island under different load characteristics.

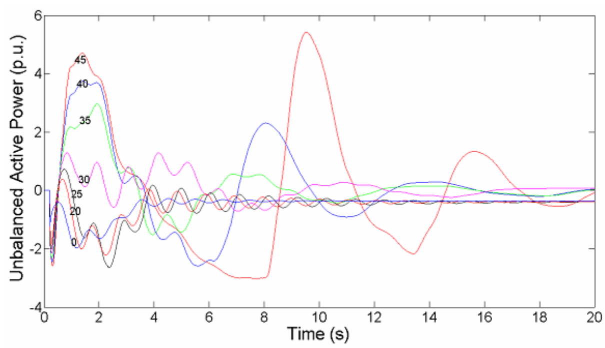

Figure 12. Comparisons of unbalanced active-power in the isolated island under different load characteristics./

4. Effects of the Coupling on Load –shedding Devices

4.1. Load-shedding Devices Installed Situations and Existing Problems

In current China's power grids underfrequency load-shedding (UFLS) and undervoltage load-shedding (UVLS) are two different kinds of devices installed to prevent frequency and voltage instability, respectively. However, these two kinds of devices are set and perform independently despite of the coupling between frequency and voltage .Lacking the coordination between them would result in excessive or insufficient control.

The UFLS and UVLS installations adopted in current Shanxi Province in China are as shown in **Table 3** and **Table 4.**

The load-shedding devices are both installed at each load node of the island.

We research control effects of the current load-shedding device on the island with the coupling of voltage and frequency.

4.2. Control Effects When ΔQ_0 Changes

Table 5 shows the control effects with different ΔQ_0, the conditions are just the same as shown in **Table 1**.

From **Table 5** it can be seen that:

1) The total shedding amount carried out by UVLS and UFLS decrease as ΔQ_0 increases.

2) The shedding amount carried out by UVLS increases as ΔQ_0, UVLS cannot start When ΔQ_0 is less than a certain threshold.

3) The shedding amount carried out by UFLS increases as ΔQ_0 decreases, UFLS cannot start When ΔQ_0 is more than a certain threshold.

Table 3. UFLS setup situations.

UFLS	Setup stages						
	I	II	III	IV	V	VI	VII
f_{set}(Hz)	49	48.8	48.6	48.4	48.2	48	49
T_{delay}(s)	0.2	0.2	0.2	0.2	0.2	0.2	10
P_{shed}(%)	7	7	7	7	7	7	4

Table 4. UVLS setup situations.

UVLS	Setup turns			
	I	II	III	IV
U_{set}(p.u.)	0.85	0.8	0.75	0.85
T_{delay}(s)	1	1	1	10
P_{shed}(%)	7	7	7	4

4) Lack of coordination between UVLS and UFLS would cause excessive control (*i.e*, f_{max}> 51 Hz) under some conditions(e.g.,ΔQ_0=1,1.5), in which low frequency and low voltage happen at the same time.

5)Currently used load-shedding relays may not prevent island from collapse under some situations(e.g. ΔQ_0 = 2,2.5),in which high frequency and low voltage happen at the same time, causing that UFLS cannot act and UVLS is too late to shed insufficient amount of load.

4.3. Control Effects When Load Characteristics Changes

Table 6 shows the control effects, the conditions are just the same as shown in **Table 2** .

What can be seen From **Table 6** are similar to those obtained from **Table 5** :

1) The total shedding amount decreases as the percentage of induction motor in load increases.

2) The shedding amount carried out by UVLS increases as the percentage, UVLS cannot start when the percentage is less than a certain threshold.

3) The shedding amount carried out by UFLS increases as the percentage decreases, UFLS cannot start when the percentage is more than a certain threshold.

4) Lack of coordinates between UVLS and UFLS would cause excessive control (*i.e*, f_{max}> 51Hz) under some situations (*e.g*., the percentage equals 30%), in

Table 5. Control effects when ΔQ_0 changes.

Codition	Control Effects					
	ΔQ_0 (p.u.)	UFLS (p.u.)	UVLS (p.u.)	f_{max} (Hz)	f_∞ (Hz)	U_{min} (p.u)
1	0.5	I-IV(4.69)	\	50.89	48.10	0.998
2	1	I-IV(4.69)	I (0.76)	51.21	48.30	0.999
3	1.5	I-III(3.52)	I,II(1.16)	51.16	48.33	0.943
4	1.6	I,II(2.35)	I,II(1.88)	50.67	48.55	0.925
5	2	\	I-IV(3.96)	51.59	49.83	0.649
6	2.5	\	I-IV(3.99)	52.34	49.94	0.576

For example, I-IV(4.69) means that UFLS performs four steps with 4.69 p.u. load shed.

Table 6. Control effects with different load characteristic.

Codition	Control Effects					
	Motor (%)	UFLS (p.u.)	UVLS (p.u.)	f_{max} (Hz)	f_∞ (Hz)	U_{min} (p.u)
1	20	I-III(3.52)	I(0.76)	50.85	49.76	0.933
2	25	I-III(3.52)	I(0.76)	50.83	48.75	0.931
3	30	I-III(3.52)	I,II(1.16)	51.11	49.99	0.967
4	35	\	I-IV(3.60)	51.56	50.66	0.628
5	40	\	I-IV(3.99)	52.35	51.17	0.606

which low frequency and low voltage happen at the same time.

5)The present UVLS and UFLS may not prevent island from collapse under some situations(*e.g*., the percentage equals 35% or 40%),in which high frequency and low voltage happens at the same time, causing that UFLS cannot act and UVLS is too late to shed insufficient amount of load.

5. Conclusions

The island frequency response is decided by both mechanical power and electromagnetic power. Island voltage affects electromagnetic power, which change the frequency dynamic in island. Initial reactive-power deficit and load characteristics are two key factors affecting the frequency response dynamic through coupling of voltage and frequency when initial active-power maintains unchanged.

When initial reactive-power or percentage of induction motor in loads increases, the voltage decreases, leading the decrease of total electromagnetic power. As the decrease of unbalanced active-power in island, the decrease of frequency decline rate and the increase of frequency. While initial reactive-power deficit or percentage of induction motor in load exceeds a certain threshold, the signal of unbalanced active-power in island would change, which may cause high frequency despite of severe active-power deficit in the island.

Ignoring the coupling of voltage and frequency dynamic would result in remarkable errors when analyzing the frequency response of the splitting island with large initial active-power deficit.

Moreover, the currently used UVLS and UFLS, whose setup and performance are independent without considering the coupling of voltage and frequency, would cause excessive when low voltage and low frequency happen at the same time or insufficient control when initial reactive-power deficit or percentage of induction motor in load exceeds a certain threshold.

It is necessary to develop coordination control for voltage and frequency on the basis of research on their coupling effects.

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