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General Aspects and Fundament of Variable Frequency Electric Power Transmission Part I: Theory

***Abstract**. This paper presented a variable frequency electric power transmission system (abbreviated as VFTS). The VFTS employs the unique variable frequency transformers (VF-transformers) to couple the transmission or distribution lines or networks to the sending and receiving systems. The VFTS changes the transmission frequency to provide unique features that cannot be obtained in the traditional ac and dc transmission systems which work on the fixed frequency. The VFTS can increase transmission capacity, improve transmission line efficiency and enhance operating performances.*

***Streszczenie.** W artykule zaprezentowano system transmisji mocy o zmiennej częstotliwości VFTS. VFTS wykorzystuje transformatory VF do sprzęgania systemów transmisji. (**Podstawy systemu VFTS – przesyłu mocy ze zmienną częstotliwością. Część I – teoria**)*

Keywords: Electronic power transformer; electric power transmission; variable frequency electric power transmission system (VFTS); variable frequency transformer.
Słowa kluczowe: bezprzewodowa transmisja mocy, system VFTS

Introduction

There exist two traditional electric power transmission systems to deliver electric power from sources (generators) to loads (customers): power-frequency alternating current (ac) and direct current (dc) electric power transmission systems. The former works at power-frequency, 50 Hz or 60 Hz, and the latter works at 0 Hz. It is obvious that they both utilize constant transmission frequency.

Fig 1(a) shows the point-to-point traditional power-frequency ac electric power transmission system (PFTS) structure. The power-frequency electric source feeds the utility grid through a step-up/-down transformer, a transmission line, and a step-down/-up transformer. For the PFTS, increasing transmission distance and capacity mainly depends on raising the voltage level of transmission lines. At present, the highest voltage level of the ac power transmission line in operation is 1000 kV [1]. The power-frequency ac transmission is the dominant mode to transfer electric power from power generators to loads in modern electric power systems. It, however, has the following conceptual and theoretical barriers and limitations.

- It is not easy for electric power with power-frequency to transfer for long distance. For long transmission length, the stability is critical. In order to enhance the stability, extra equipments are needed.
- The whole system should be synchronized under the same frequency, 50 Hz or 60 Hz.
- The transmission capacity is limited by many factors.
  - There are huge capacitance currents when underground/ undersea cables are used. This results in decrease of the transmission capacity and increase of the transmission loss.

Fig 1 (b) shows the traditional dc electric power transmission system (DCTS) structure. The power-frequency electric source feeds the utility grid through a step-up/-down converter station, a transmission line, and a step-down/-up converter station. Here, the electric source and utility grid work at power-frequency, and the transmission line works at 0 Hz. The now highest voltage level of the dc transmission line in operation is ±800 kV [2]. However, the dc transmission system has the following conceptual and theoretical barriers and limitations.

- It is unable to change voltage levels in dc networks by transformer.
- Converter substations generate current and voltage harmonics, while the conversion process is accompanied by large reactive power consumption. As a result, it is necessary to install expensive filter-compensation units and reactive power compensation units.
- High voltage dc circuit breakers are difficult to build because some mechanism must be included in the circuit breaker to force current to zero, otherwise arcing and contact wear would be too great to allow reliable switching. This results that realizing multi-terminal systems is very difficult.

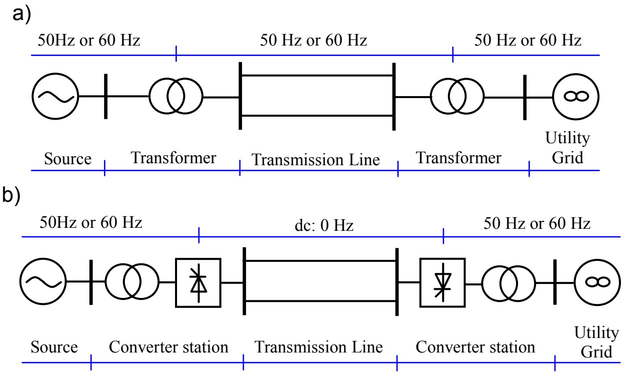

Fig. 1. Traditional electric power transmission system based on power-frequency ac (a) and on dc (b)

In addition, both the PFTS and DCTS have the common problem: They cannot obtain optimal operating performances, such as efficiency and voltage profile, by themselves when the operating condition, such as load flow level, changes.

Although people do not want reactive power to be transmitted through transmission lines, reactive power flow does exist. Because there is series reactance, the transmission line must consume reactive power when electric power transfer arises. On the other hand, because there are the capacitance effects between the transmission lines and the neighboring conductors, the transmission lines will generate reactive power under potential exciting. So, the transmission lines have different reactive power characteristics with different load levels. From the viewpoint of operation and control, the control of electric power of the transmission line is the reactive power control on the condition of specified real power. For the traditional PFTS, to improve power transmission capacity and maintain voltage levels through along transmission line, reactive power compensation is often the most effective way.

Nowadays, people have recognized that energy conservation has significant economic, social, and environmental benefits. Electrical energy conservation is an important element of energy saving. Many efforts have been made to improve transmission system efficiency and reducing carbon emissions [3]. It is interesting to find out new methods to reduce the power losses of electric networks (transmission networks and distribution networks).

To overcome or alleviate the above problems of the traditional fixed frequency transmission system, this paper proposes a novel electric power delivery method of variable frequency electric power transmission system (VFTS).

Variable Frequency Electric Power Transmission System

Fig. 2 shows the general VFTS structure. It is quite similar to the traditional PFTS. The difference is that it employs the variable frequency transformer (VF-transformer) to replace the power-frequency transformer. The function of VF-transformer is not only changing voltage level, but also changing transmission frequency and/or phase.

The unique feature of the VFTS is that the transmission frequency can be any value (in theory) regardless of the frequencies of the electric source and utility grid. That is, the source and grid frequencies may be variable or be any specified values, and the transmission frequency can vary in a range under different operation conditions. Therefore, VFTS can be used for interconnecting various different electric powers, such as constant ac, variable frequency ac, dc, etc., which are provided by distributed sources, such as micro-turbines, wind turbines, photovoltaic (PV) arrays, and fuel cells. In this paper, however, as an example, only power-frequency of 50 Hz is considered for two ends.

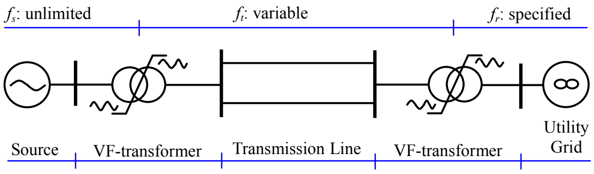

Fig.2. Structure of the variable frequency electric power transmission system.

Although references [4] and [5] discussed changing transmission frequency from 50Hz to lower than 20 Hz (called as fractional frequency transmission or low frequency ac transmission) to reduce dominated reactance or susceptance of transmission line, this transmission technology is still fixed frequency transmission. The VFTS will change transmission frequency timely according to the factual operation conditions to catch optimal operating performances.

Generally, VFTS is a fundamental concept. The traditional power-frequency or low frequency ac and dc electric power transmission systems can be regarded as special cases with constant transmission frequency.

The key unit in VFTS is the VF-transformer. Its feature is crucial to the feasibility of the whole VFTS. The VF-transformer should be capable of changing the frequency flexibly and easily.

It is very difficult for transmission and distribution systems to change the operating frequency in the past. However, the situation has been improving recently. An asynchronous rotating machine named variable frequency transformer (VFT) has been presented in [6]. The VFT can be used to connect two asynchronous power systems. On the other hand, the advancement of power electronics based transformer topologies and control provides a basis for varying transmission frequency [7-10-. Power electronics based transformer is also named electronic power transformer (EPT), solid-state transformer (SST), electronic transformer, and power electronic transformer (PET). It utilizes power electronic converters along with a high-frequency transformer to obtain overall size and cost ascendancies over a conventional transformer and/or achieve the functions of flexible ac transmission systems (FACTS) or DFACTS [11]. In addition, its unique features are realizing flexible frequency variation and phase modulation along with changing voltage level. So, EPT can be regarded as a static variable frequency transformer. Compared with VFT, EPT has wide frequency change range and fast response speed, and does not have any rotating part.

Although there is not the high-voltage and high-power EPT in the industrial application, it has clear realization possibility. Recently, the utilization of high-voltage and high-power power electronic based devices and equipments have been growing widely in electric power systems with the advancement of power electronics circuits and devices. Nowadays, about a hundred thyristor-based high voltage direct current (HVDC) systems and many FACTS devices are serving and improving the performances of electric power systems. It is believed that the high rating EPT would serve soon.

Fig. 3 shows an EPT based VFTS for two regional power grids interconnecting. We will discuss this example in detail. For the analysis of the VFTS, the mathematical models of VF-transformer and transmission line are important.

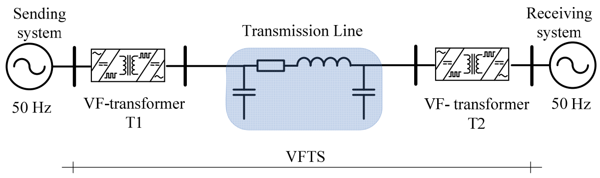

Fig.3. VFTS for two regional power grid interconnecting.

Fundamental Model of Long Homogeneous Transmission Line

The parameters of a homogeneous transmission line are uniformly distributed. A transmission line is characterized by four distributed circuit parameters: per-unit-length series resistance (r) and inductance (l), and shunt conductance (g) and capacitance (c), as shown in Fig. 4. The four parameters are functions of the line design, that is, of the conductor size, type, space, height above ground, frequency, and temperature. The characteristic behavior of the line is dominated by the series inductance and shunt capacitance. Series resistance has a secondary but not insignificant influence, and has a separate importance in determining losses. Although the distributed circuit parameters are not independent of frequency, they trend to constant if the frequency is "high" enough ($\omega >> r / l$) [12]. In this paper, they are assumed fixed because the operation frequency is in a restricted range of "high" enough. Another reason is that they change little or/and slow with frequency [12].

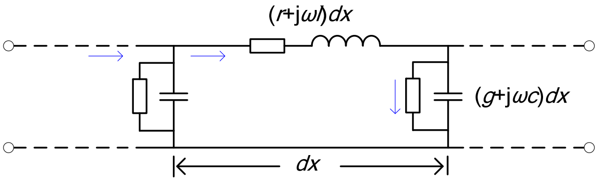

Fig.4. Circuit model for homogeneous transmission line.

According to the model shown in Fig.4, the generalized equations for steady-state sinusoidal waves are [15]

$$\left.\begin{aligned}\frac{d\dot{V}}{dx}&=\left(r+\mathrm{j}\omega l\right)\dot{I}\\ \frac{d\dot{I}}{dx}&=\left(g+\mathrm{j}\omega c\right)\dot{V}\end{aligned}\right\} \quad (1)$$

where *V* and *I* are the position-dependent voltage and current along the line, respectively.

The conductance g accounts line losses due to leakage currents between conductors or between conductors and ground. Usually, it is small enough for a well-designed case to be omitted. So, (1)is modified:

$$\left.\begin{aligned}\frac{d\dot{V}}{dx}&=\left(r+\mathrm{j}\omega l\right)\dot{I}\\ \frac{d\dot{I}}{dx}&=\left(\mathrm{j}\omega c\right)\dot{V}\end{aligned}\right\} \quad (2)$$

It is complicated to do the calculation and analysis by the distributed parameters. So the lumped parameter equivalent circuits are usually used. The lumped equivalent circuit parameters of any length of transmission line can be obtained by using above equations under setting boundary conditions. Generally, for long transmission lengthen, to account the distributed nature to obtain exact behavior and to satisfy the demand of analyzing voltage distribution along the line, it is necessary to use several cascading cells of equivalent π circuits to equal a long transmission line, as shown in Fig. 5. Here, the physical length that each cell indicates must be smaller than a quarter of wavelength, satisfying the rule-of-thumb effective-homogeneity condition [13].

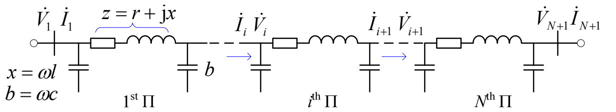

Fig.5. Lumped element representation of a long transmission line.

Equivalent Circuit And Operating Principle Of VFTS

Nowadays, extra-high voltage (EHV) and ultra-high voltage (UHV) overhead transmission lines are used for long distance electric power transmission. A severe "Ferranti Effect" is very easy to arise for EHV and UHV transmission lines, because surplus reactive power is too high, which results from the high operation voltages. When load is dropped, the voltage rise will also be severe to cause problems for insulation or for voltage regulating equipment. So, shunt reactors are usually employed for EHV/UHV lines to compensate the high charging current, which not only prevents overvoltage during load dropping but also improves conditions for load flow [15]. The shunt reactors are usually located at one or both terminals and the intermediate station.

On the other hand, in the load center, the enlarging urban, and in the traction system, the underground power cable transmission trends to be adopted more in the future for avoiding spoiling the landscape and the environmental and ecological suspicion to the electric magnetic field induced by the power line. However, power cable has large shunt capacitance which increases with cable length. This induces a large charging current. When the length is long enough, the charging current is huge so that no real power can be transmitted. Therefore, to have maximum transmissible length, the power cable must be compensated from one or both terminals by shunt reactors or other devices.

Thus, a practical transmission line system is constructed by overhead lines or power cables and shunt reactors. We modified the structure in Fig. 3 with the transmission line modeled by cascading cells of equivalent π circuits. The revised VFTS structure is shown in Fig. 6. It consists of sending system (regional power grid or generator), VF-transformers T1 and T2, shunt reactors L1 and L2, transmission line, and receiving system (regional power grid or load). Its operation principle is as follows: (1) firstly, the sending system operates at specified voltage and power-frequency (*E_s*, 50 Hz); (2) and then, the electricity is conversed to another special voltage and optimal frequency (V_s, f_t) by T1 and is transmitted to T2; (3) finally, it is converted to the voltage level and power-frequency (E_r, 50 Hz) required by the receiving system and is injected into the receiving system. As mentioned earlier, it is considered that only the frequency of the transmission line is variable but the frequencies of the two end systems are constant. When the power flow through the line changes, a new optimal transmission frequency reference will be obtained and used.

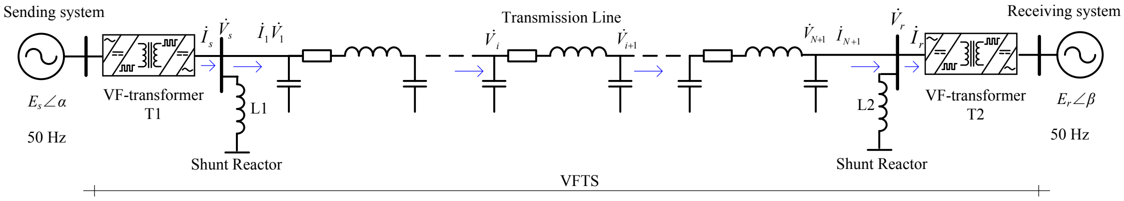

Fig.6. Structure of VFTS example.

Mathematical model of VFTS

The mathematic model of VFTS consists of two parts: EPT (static VF-transformer) model and transmission line model.

As stated in [14], the steady-state models of EPTs, T1 and T2, can be described as:

$$0=Z_{\mathrm{T1}}\dot{I}_{\mathrm{s}}+\dot{V}_{\mathrm{s}}-\dot{V}_{\mathrm{T1}} \quad (3)$$

$$0=-Z_{\mathrm{T2}}\dot{I}_{\mathrm{r}}+\dot{V}_{\mathrm{r}}-\dot{V}_{\mathrm{T2}} \quad (1)$$

where Z_{T1} and Z_{T2} are the equivalent interface impedances of T1 and T2, respectively, V_{T1} and V_{T2} are the inner ac terminal voltages of T1 and T2, respectively, and V_{s} and V_{r} are the voltages of sending receiving ends. In addition, the inner ac terminal voltages, V_{T1} and V_{T2}, could be regulated easily and flexibly.

For the transmission line, the following equations are satisfied from Fig. 5.

$$\begin{bmatrix}\dot{V}_i\\ \dot{I}_i\end{bmatrix} = \begin{bmatrix}1+\mathrm{j}bz & z\\ (2+\mathrm{j}bz)\mathrm{j}\omega c & 1+\mathrm{j}bz\end{bmatrix}\begin{bmatrix}\dot{V}_{i+1}\\ \dot{I}_{i+1}\end{bmatrix} = \begin{bmatrix}1+\mathrm{j}bz & z\\ (2+\mathrm{j}bz)\mathrm{j}\omega c & 1+\mathrm{j}bz\end{bmatrix}^{N+1-i}\begin{bmatrix}\dot{V}_{N+1}\\ \dot{I}_{N+1}\end{bmatrix} \tag{5}$$

$$\begin{bmatrix}\dot{V}_1\\ \dot{I}_1\end{bmatrix} = \begin{bmatrix}1+\mathrm{j}bz & z\\ (2+\mathrm{j}bz)\mathrm{j}\omega c & 1+\mathrm{j}bz\end{bmatrix}^{N}\begin{bmatrix}\dot{V}_{N+1}\\ \dot{I}_{N+1}\end{bmatrix} \tag{6}$$

where $b=\omega c$, $x=\omega l$, and $z=r+jx$.

Thus, the steady-state model of VFTS can be given by the following equations if considering the effect of shunt reactors:

$$\begin{cases}\begin{bmatrix}\dot{V}_{T1}\\ \dot{I}_{T1}\end{bmatrix} = \begin{bmatrix}1 & Z_{T1}\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 1/(j\omega L_1) & 1\end{bmatrix}\begin{bmatrix}\dot{V}_1\\ \dot{I}_1\end{bmatrix}\\ \begin{bmatrix}\dot{V}_i\\ \dot{I}_i\end{bmatrix} = \begin{bmatrix}1+\mathrm{j}bz & z\\ (2+\mathrm{j}bz)\mathrm{j}\omega c & 1+\mathrm{j}bz\end{bmatrix}^{N+1-i}\begin{bmatrix}\dot{V}_{N+1}\\ \dot{I}_{N+1}\end{bmatrix}\\ \begin{bmatrix}\dot{V}_{N+1}\\ \dot{I}_{N+1}\end{bmatrix} = \begin{bmatrix}1 & 0\\ 1/(j\omega L_2) & 1\end{bmatrix}\begin{bmatrix}1 & Z_{T2}\\ 0 & 1\end{bmatrix}\begin{bmatrix}\dot{V}_{T2}\\ \dot{I}_{T2}\end{bmatrix}\end{cases} \tag{7}$$

The voltage distribution can be calculated from (5) with the specified voltage and current of the receiving end.

The real and reactive power losses can also be calculated as follows:

$$\begin{aligned}P_{loss} &= \sum p_{loss} = \sum_{i=1}^{N}\left|\dot{I}_i - \dot{V}_i\cdot \mathrm{j}b\right|^2 r\\ &= \sum_{i=1}^{N}\left|\dot{I}_{i+1} + \dot{V}_{i+1}\cdot \mathrm{j}b\right|^2 r = \sum_{i=1}^{N}\left|\begin{bmatrix}-\mathrm{j}b & 1\end{bmatrix}\begin{bmatrix}\dot{V}_i\\ \dot{I}_i\end{bmatrix}\right|^2 r\end{aligned} \tag{8}$$

$$\begin{aligned}Q_{loss} = \sum q_{loss} = \sum_{i=1}^{N}\Bigg\{&\left|\begin{bmatrix}-\mathrm{j}b & 1\end{bmatrix}\begin{bmatrix}\dot{V}_i\\ \dot{I}_i\end{bmatrix}\right|^2\cdot x\\ &-\left[V_i^2 + \left|\begin{bmatrix}1+\mathrm{j}bz & -z\end{bmatrix}\begin{bmatrix}\dot{V}_i\\ \dot{I}_i\end{bmatrix}\right|^2\right]\cdot b\Bigg\}\end{aligned} \tag{9}$$

As shown in (5) ~(9), not only the load flow but also the series impedance and shunt susceptance have influences on the voltage profile and power losses. Because the values of impedance and susceptance depend on frequency, it is possible to reduce the line power losses and improve the voltage distribution by changing the transmission frequency. At the same time, the modification of the transmission frequency has an influence on the transmission capacity. For example, the fractional frequency transmission system is to reduce the transmission frequency to increase its power transmission capacity [4].

Advantages of VFTS

The VFTS proposed in this paper is aiming at transmitting large power with high performances. Its advantages are summarized as follows, when comparing it to traditional fixed frequency transmission systems.

1) Enhance the rotor angle stability of electric power systems. The VFTS is decoupled from external electric power systems for VF-transformer regulating. That is, if two groups of machines are connected by a VFTS, there is no synchronism issue between them. For the PFTS, however, the two groups of machines are coupled tightly and stiffly. Loss of synchronism means the system should be disconnected.

It should be noted that the transmission line rotor angle stability issue exists yet for VFTS, just like the traditional ac transmission line. As shown in Fig.6, the transmitted power by the transmission line is given by

$$P_t = \frac{V_s V_r}{Z_t}\sin\delta = P_{\max}\sin\delta \tag{10}$$

where *δ* is the phase angle difference between V_s and V_r, and Z_t is the transmission line impedance.

It is clear from (10) that the maximum power is a function of the voltages of two terminals, and more importantly, a function of the transmission line impedance which is dominated by the frequency. For the traditional fixed frequency ac electric power transmission system, the maximum power is constant. The VFTS can change the frequency to change the line impedance. Therefore, the maximum power can be varied according to the demand. This means the VFTS will have the sufficient stability margin in much wider transmitted power range compared to the fixed frequency transmission system.

2) Make power flow control flexible. It is difficult to control rapidly the power flow of the traditional fixed frequency ac system without any assistance of FACTS facilities, because both real and reactive power flow must be considered simultaneously, which is dominated by slow action of the rotating synchronous machine. However, the swift real and reactive power flow control is available for VFTS by the operation of the VF-transformer.

3) Improve transmission line efficiency. Not only real power but also reactive power will induce power losses when they flow through the transmission line because there is the series resistance. The transmission line must consume reactive power when power flowing through it since there is the series inductive reactance. On the other hand, the transmission line will generate reactive power because of capacitance effects between the transmission line and the neighboring conductors. The reactive power difference dominates the voltage profiles along the transmission line. For the fixed frequency ac electric power transmission system, the reactive power difference varies largely when the real power flow changing. To guarantee the voltage on the safe level, a large quantity of reactive power should be provided or absorbed by the terminals, which causes additional line power losses. Fortunately, the VFTS can minimize the reactive power difference between the series inductance and shunt capacitance by varying the transmission frequency with the real power flow changing. This results in the power losses reducing. So, the transmission line efficiency is improved.

4) Increase utilization factor of a transmission line. The transmission line of the VFTS is the same as that of the traditional ac transmission system having 3-phase configuration. Its transmitting instantaneous power is constant, which is the same as a conventional 3-phase ac

system. As analyzed above, the maximum power of VFTS will be larger than that of traditional ac systems, when the frequency of the former is lower than the frequency of the latter. So, the utilization factor of a transmission line of VFTS can be higher than that of the traditional ac transmission system.

Conclusion

This paper has presented a variable frequency transmission system for electric power delivery. The VFTS employs the special transformers with the function of variable voltage and frequency to change the transmission frequency according to the line loading level, thus providing better operating performances, such as larger transmission capacity, higher stable level, higher transmission line efficiency, etc.. In theory, the VFTS can be applied to the entire spectrum of ac transmission and distribution systems. The VFTS concept is general and can be used for introducing a unified theory of electric power transmission between the power-frequency transmission and dc transmission technologies.

If we remove the shunt reactors and aim power loss reduction, there is an interesting phenomenon that the VFTS system will evolve into a dc transmission system from an ac transmission system. It is obvious that the power losses are minimized if electricity is transmitted by dc, because the current through the resistor is minimum for the transmission line does not generate and consume reactive power. However, dc transmission has its difficulties, as stated in Section 1. In addition, for the three-wire transmission system, it is not an economic choice to use dc transmission since only two wires are utilized. Furthermore, the shunt inductors have been installed in extra- and ultra-high voltage transmission lines and it means dc power transmission is unavailable.

Nowadays, the traditional dc transmission has been an economical means to bring the electricity from remote energy sources to load centers. However, because of the limitation on the breaker and inability to use transformers to alter voltage levels, the applications of dc transmission are limited.

If the transferred real power varies significantly and frequently, or generators have higher efficiency under variable frequency, the VFTS may be a competitive method. The first applications for VFTS may be: 1) the situation where the delivered real power varies significantly, such as area tied-line; 2) and the situation where the generators have higher efficiency if they operated under variable frequency, such as wind farm, pumped storage power station, and hydropower station. In situation 2, the VFTS can save a VF-transformer, thus reducing investment.

Acknowledgements

This work was supported in part by the National Nature Science Foundation of China (50807020), SRF for ROCS, SEM, and the Fundamental Research Funds for the Central Universities of China (2010QN025).

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