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General Aspects and Fundament of Variable Frequency Electric Power Transmission Part II: Study Case

***Abstract**. The variable frequency electric power transmission system (abbreviated as VFTS) can increase transmission capacity, improve transmission line efficiency and enhance operating performances. To describe the operating principle, this paper focused on an example: a VFTS for interconnecting two regional power grids/sources far apart applications, to explore the steady state characteristics. Simulation results are presented to demonstrate the new features.*

***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 II – Realizacja**)*

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

Both the traditional power-frequency ac electric power transmission system (PFTS) and dc electric power transmission system (DCTS) have the common problem: They cannot obtain optimal operating performances, such as efficiency and voltage profile, by themselves when the operation condition, such as load flow level, changes. To overcome or alleviate the problems of the traditional fixed frequency transmission system, we have proposed a novel electric power delivery method of variable frequency electric power transmission system (VFTS) in the paper [1], which constitutes the first part of the present work. The Part II focuses on a study case to show the characteristics of the VFTS.

Study case

Based on the analysis in [1], let us find out a practical case for the analysis of VFTS. The first 1000 kV UHV test transmission line in China is used to link the southeastern parts of coal-rich Shanxi Province with Jingmen city in energy-guzzling Hubei Province, by-passing Nanyang city in Central China's Henan Province. The transmission distance between Southeast Shanxi (Jindongnan) and Nanyang is about 360 km and the distance between Nanyang and Jingmen is about 285 km. To absorb the excess reactive power, the shunt reactors are permanently connected at the three locations. We consider the VFTS based on UHV transmission line as a study case.

The model of the UHV line is shown in Fig.1. And the parameters are shown in Table 1 and Table 2 [2].

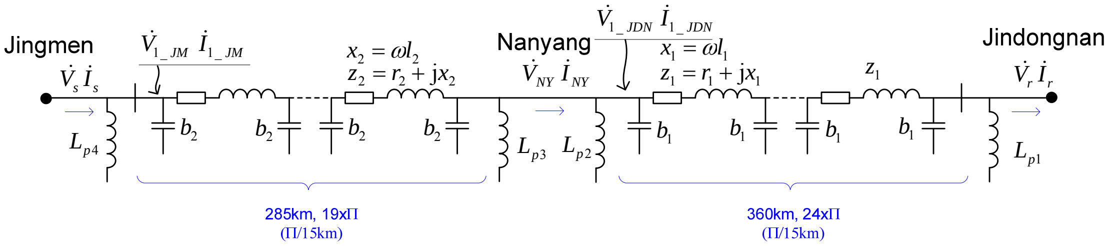


Fig.1. UHV transmission line model.

Table 1 Per-unit-length circuit parameters*

Line	R/Ω	L/H	C/μF	φ/°
Jindongnan - Nanyang	0.1137	0.01259	0.104775×2	88.35
Nanyang - Jingmen	0.12015	0.01257	0.103725×2	88.25

* Per-unit-length means the distance denoted by an equivalent π circuit. Here it is 15 km.

Table 2 The parameters of shunt reactors**

Line	Location	Capacity Mvar	R/Ω	Voltage/kV
Jindongnan - Nanyang	Jindongnan	960	1260	1100
	Nanyang	720	1680	1100
Nanyang - Jingmen	Nanyang	720	1680	1100
	Jingmen	600	2016	1100

** The value at specified frequency, 50 Hz.

According to the π circuit mathematical model derived in Part I, the mathematical model of UHV transmission lines can be written as follows.

(1) The distributions of voltage and current of NanYang-Jindongnan section:

$$\begin{bmatrix}\dot{V}_{i\_JDN}\\ \dot{I}_{i\_JDN}\end{bmatrix}=\begin{bmatrix}1+jb_1z_1 & z_1\\ (2+jb_1z_1)\,jb_1 & 1+jb_1z_1\end{bmatrix}^{25-i}\cdot\begin{bmatrix}1 & 0\\ 1/j\omega L_{p1} & 1\end{bmatrix}\begin{bmatrix}\dot{V}_r\\ \dot{I}_r\end{bmatrix}\tag{1}$$

(2) The distributions of voltage and current of Jingmen-Nanyang section:

$$\begin{bmatrix}\dot{V}_{i\_JM}\\ \dot{I}_{i\_JM}\end{bmatrix}=\begin{bmatrix}1+\mathrm{j}b_2z_2 & z_2\\ (2+\mathrm{j}b_2z_2)\,\mathrm{j}b_2 & 1+\mathrm{j}b_2z_2\end{bmatrix}^{20-i}$$

$$\cdot\begin{bmatrix}1 & 0\\ 1/\mathrm{j}\omega L_{p3} & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 1/\mathrm{j}\omega L_{p2} & 1\end{bmatrix} \tag{2}$$

$$\cdot\begin{bmatrix}1+\mathrm{j}b_1z_1 & z_1\\ (2+\mathrm{j}b_1z_1)\,\mathrm{j}b_1 & 1+b_1z_1\end{bmatrix}^{25}$$

$$\cdot\begin{bmatrix}1 & 0\\ 1/\mathrm{j}\omega L_{p1} & 1\end{bmatrix}\begin{bmatrix}\dot{V}_r\\ \dot{I}_r\end{bmatrix}$$

$$\begin{bmatrix}\dot{V}_s\\ \dot{I}_s\end{bmatrix}=\begin{bmatrix}1 & 0\\ 1/\mathrm{j}\omega L_{p4} & 1\end{bmatrix}\begin{bmatrix}1+\mathrm{j}b_2z_2 & z_2\\ (2+\mathrm{j}b_2z_2)\,\mathrm{j}b_2 & 1+\mathrm{j}b_2z_2\end{bmatrix}^{20}$$

$$\cdot\begin{bmatrix}1 & 0\\ 1/\mathrm{j}\omega L_{p3} & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 1/\mathrm{j}\omega L_{p2} & 1\end{bmatrix}$$

$$\cdot\begin{bmatrix}1+\mathrm{j}b_1z_1 & z_1\\ (2+\mathrm{j}b_1z_1)\,\mathrm{j}b_1 & 1+b_1z_1\end{bmatrix}^{25}\begin{bmatrix}1 & 0\\ 1/\mathrm{j}\omega L_{p1} & 1\end{bmatrix}\begin{bmatrix}\dot{V}_r\\ \dot{I}_r\end{bmatrix}$$

(3) The line power losses:

$$P_{loss}=\sum p_{loss}=\sum_{i=1}^{24}\left|\begin{bmatrix}-\mathrm{j}b_1 & 1\end{bmatrix}\begin{bmatrix}\dot{V}_{i\_JDN}\\ \dot{I}_{i\_JDN}\end{bmatrix}\right|^2 r_1 \tag{3}$$

$$+\sum_{i=1}^{19}\left|\begin{bmatrix}-\mathrm{j}b_2 & 1\end{bmatrix}\begin{bmatrix}\dot{V}_{i\_JM}\\ \dot{I}_{i\_JM}\end{bmatrix}\right|^2 r_2$$

$$Q_{loss}=\sum q_{loss}=\sum_{i=1}^{24}\left\{\left|\begin{bmatrix}-\mathrm{j}b_1 & 1\end{bmatrix}\begin{bmatrix}\dot{V}_{i\_JDN}\\ \dot{I}_{i\_JDN}\end{bmatrix}\right|^2 x_1\right.$$

$$\left.-\left[V_{i\_JDN}^2+\left|\begin{bmatrix}1+\mathrm{j}b_1z_1 & -z_1\end{bmatrix}\begin{bmatrix}\dot{V}_{i\_JDN}\\ \dot{I}_{i\_JDN}\end{bmatrix}\right|^2\right]\cdot b_1\right\} \tag{4}$$

$$+\sum_{i=1}^{19}\left\{\left|\begin{bmatrix}-\mathrm{j}b_2 & 1\end{bmatrix}\begin{bmatrix}\dot{V}_{i\_JM}\\ \dot{I}_{i\_JM}\end{bmatrix}\right|^2 x_2\right.$$

$$\left.-\left[V_{i\_JM}^2+\left|\begin{bmatrix}1+\mathrm{j}b_2z_2 & -z_2\end{bmatrix}\begin{bmatrix}\dot{V}_{i\_JM}\\ \dot{I}_{i\_JM}\end{bmatrix}\right|^2\right]\cdot b_2\right\}$$

Simulation Results

The first is to verify using VFTS to increase the utilization factor of a transmission line. The best way is to examine its power-angle curves. We carried out simulations for the VFTS based on UHV line model shown in Fig.1, keeping all the boundary conditions unchanged but the voltage phase angle at the receiving end.

Fig. 2 shows the power-angle curves of the VFTS with different transmission frequencies, such as 50 Hz, 40 Hz and 25 Hz. The curves indicate that the VFTS could increase the transmission capacity by decreasing the frequency. That is, the utilization factor of a transmission is improved. Fig. 2 also implies that, for any power flow, VFTS could always obtain sufficient stability margin by changing the operating frequency, and achieve higher operation performances. For example, when transmitted real power changes from P_1 to P_2, the transmission frequency of the VFTS may be changed from 50 Hz to 40 Hz to achieve sufficient stability margin. But the performance of PFTS will be degraded because of too small stability margin.

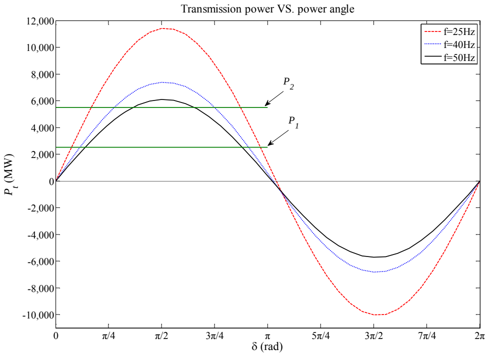


Fig.2. Power-angle curves of VFTS with different transmission frequency.

Now, let us focus on to verify how to guarantee the voltage profile and to improve transmission line efficiency by varying the transmission frequency. The operation of VFTS can be treated as an optimization problem: find out an optimal operating frequency according to the different operation conditions. In order to guarantee the voltage profile along the line and reduce the line power losses, the following objective function is used

$$F=\min\left|P_{\mathrm{loss}}+\lambda\sum_{\mathrm{i}=1}^{\mathrm{n}}\left|\Delta V_{\mathrm{i}}/\Delta V_{\mathrm{im}}\right|^2\right| \tag{1}$$

where, λ is the penalty factor. And

$$\Delta V_{\mathrm{i}}=\begin{cases}V_{\mathrm{i\,min}}-V_{\mathrm{i}} & V_{\mathrm{i}}<V_{\mathrm{imin}}\\ 0 & V_{\mathrm{imin}}\le V_{\mathrm{i}}\le V_{\mathrm{imax}}\\ V_{\mathrm{i}}-V_{\mathrm{i\,max}} & V_{\mathrm{i}}>V_{\mathrm{imax}}\end{cases} \tag{2}$$

$$\Delta V_{\mathrm{im}}=V_{\mathrm{imax}}-V_{\mathrm{imin}}$$

It denotes the limits on dependent variables (non-control variables) which must be achieved through control scheduling while improving the operating objective.

Another constrain condition is

$$0\le I_{Lpi}\le I_{Lpi\ \max} \tag{3}$$

It denotes the security limits (limits on shunt reactors' currents) that must be satisfied through control scheduling while improving the operating objective.

According to Fig.1, simulations are performed to confirm the above analysis. In the simulations, the parameters of the first 1000 kV UHV test transmission line are used. Generally, the ac resistance of any conductor depends on the frequency of the current through it, which influenced by the skin effect. So, in the simulation, the skin effect is taken into account. The detailed explanation is shown in the appendix. For comparison, a PFTS (at 50 Hz) with continuous reactive power compensation is also simulated. Fig. 3~ Fig. 6 show the simulation results.

Fig.3 indicates that the optimal transmission frequency of the VFTS varied from about 42 Hz to 72 Hz when the load flow changing from lightness to heaviness. Correspondingly, the line power losses of the VFTS are reduced markedly compared with that of the PFTS, since the operation frequency is changed, as shown in Fig.4.

Fig. 5 demonstrates that the voltages along the line have good profiles in the VFTS though the loads change in a large range (from light load to heavy load). The reason is that the VFTS has optimized reactive power supply/consumption and the mandatory voltage limitation is applied in the optimization. Similarly, the voltage profiles in the PFTS are satisfactory because of the ample reactive power supplies and the mandatory voltage limitations.

Fig. 6 shows the reactive power at the sending and receiving ends. Compared with the PFTS, it can be seen that the VFTS consumes (or produces) small reactive power which can be provided (or absorbed) directly by EPTs (VF-transformers). However, the PFTS not only consumes large reactive power, but also need be equipped with extra large capacity reactive power compensation devices.

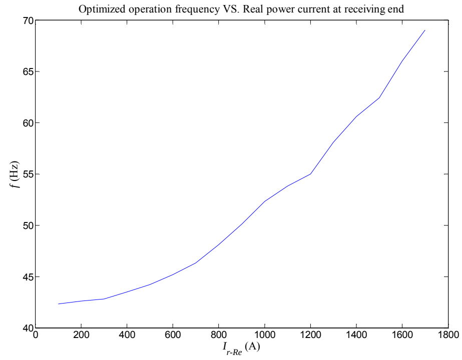
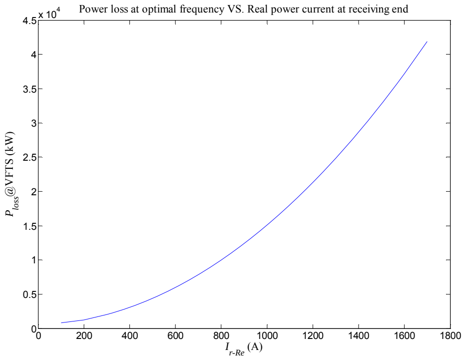
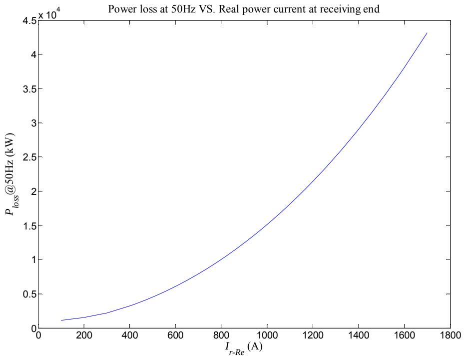


Fig. 3. The optimal operation frequency curve of VFTS under different load flow levels

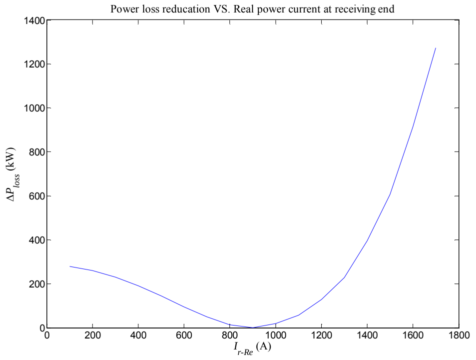
a) Power loss in VFTS



b) Power loss in PFTS with continuous reactive power compensation



c) Power loss reduction



d) Power loss reduction in percent

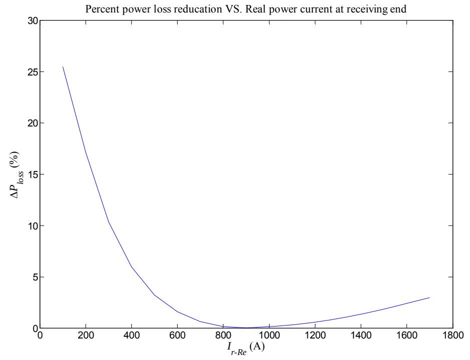
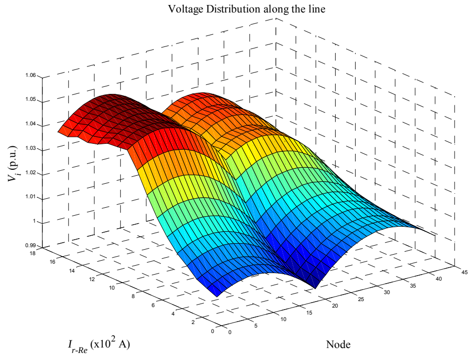


Fig. 4. Line power loss reduction when VFTS is compared to the fixed frequency (50 Hz) transmission system.

a) Voltage profiles in VFTS



b) Voltage profiles in PFTS with continuous reactive power compensation

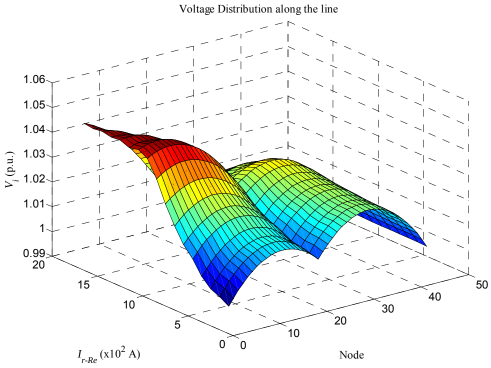
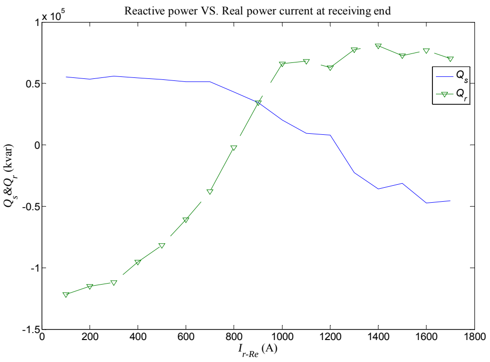


Fig. 5. Voltage distribution along the transmission line under different load conditions.

a) Required Reactive power in VFTS



b) Required reactive power in PFTS with continuous reactive power compensation

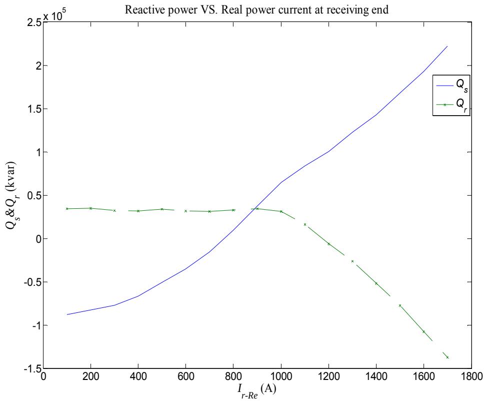


Fig. 6. Reactive power at sending and receiving ends.

Conclusion

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.

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.. This paper just presented preliminary results of VFTS. The further investigation should be done, such as a study on economic feasibility, comprehensive comparison of HVDC, PFTS and VFTS on costs, technical considerations and the reliability/availability, analysis of transient and dynamic stability, and so on. Based on the general theory developed in the Part I, the present paper carries out some simulations. Some results are given to demonstrate the feasibility of VFTS.

Appendix

There are two overhead wires, LGJ-500/35 and LGJ-500/45, used in the 1000 kV UHV ac transmission system. The ac resistance of any conductor depends on the frequency of the current through it, since this determines the skin effect. Reference [3] stated how to consider the skin effect to correct the ac resistance of the conductor. Based on the method given in [3], the skin effect is taken into account in the simulations. The calculation results of the ratio of ac resistance to that at power frequency (50 Hz) are shown in Fig. A1.

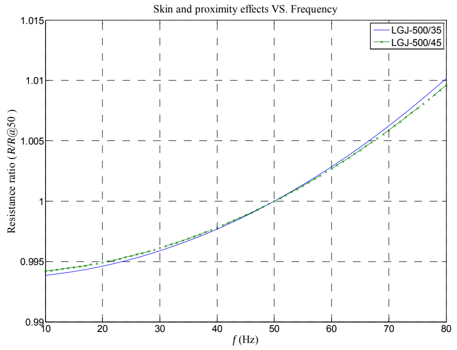


Fig. A1 Variation of the resistance ratio of UHV conductors with frequency

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