Variable Frequency Half-Wavelength Transmission Scheme

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Abstract—The half-wavelength transmission technology is attracting more and more attentions by its unique economic and technological advantages. This letter proposes a novel transmission scheme, variable frequency half-wavelength transmission scheme, to extend the application of traditional half-wavelength transmission technology. The idea is to change the frequency of transmitted power, thus changing the required line length. Feasibility study is carried out. The result shows contemporary technology is ready for the proposed transmission scheme.

Index Terms—Half-wavelength transmission technology, variable frequency power generator, frequency changer.

I. INTRODUCTION

Half-wavelength transmission line (HWTL) means that the line length between the sending and receiving ends is about half of a power frequency wavelength. Power transmission at this distance has some attractive features, like extremely stable end voltage, large power transmission capacity, and no compensating equipments and switching stations required [1].

Normally, the natural HWTL (2500km at 60 Hz) is too long for practical use. Conventional solution is to use artificial compensation like Pi tuning, T tuning and capacitor tuning. The artificial line does have the inherent advantages of natural HWTL, but some side effects emerge sequentially. For example, the line-end tuning banks experience high overvoltage when loads greater than surge impedance loading (SIL) are transmitted; A minimum of two switching stations will be necessary when Pi or T tuning banks are provided for a double-circuit line to ensure transient stability [2].

With the development of power electronic technology, half-wavelength transmission technology could be more flexible to use by changing the frequency of power, which consequently changes the corresponding HWTL length. To achieve this goal, a new transmission scheme, variable frequency half-wavelength transmission scheme, is proposed in this letter. Feasibility study result is also presented, which shows the proposed scheme is practical to implement.

II. PROPOSED SCHEME

Compared with reactive parts of the transmission line, resistance and conductance are negligible, so the line can be approximately regarded as lossless. According to the sinusoidal steady-state solution of the lossless transmission line equation, the voltage and current vector at distance \( x \) from the receiving end is given by the equation:

\[
\begin{bmatrix}
U \\
I
\end{bmatrix} =
\begin{bmatrix}
\cos \alpha x & \frac{1}{Z_c} \sin \alpha x \\
\frac{1}{Z_c} \sin \alpha x & \cos \alpha x
\end{bmatrix}
\begin{bmatrix}
U_r \\
I_r
\end{bmatrix}
\]

(1)

where \( Z_c \) is surge impedance and \( \alpha \) is phase constant given by \( \alpha = \frac{2\pi}{\lambda} \) (\( \lambda \) is wavelength).

Hence, the end voltages and currents of a \( \lambda/2 \) line can be derived as (2), which is the key advantage of half-wavelength transmission technology:

\[
V_i = -V_r; I_i = -I_r
\]

(2)

As aforementioned, the main drawback of natural HWTL is its fixed improper length. To overcome this problem, one solution is to change the frequency of power. As we know, the electrical wavelength is determined by the frequency of transmitted power as \( \lambda = \frac{\nu}{f} \), where \( \nu \) is the wave propagation speed and close to \( 3 \times 10^8 \) m/s, and \( f \) is the frequency of power. If the frequency of power is raised, the corresponding length of HWTL will be reduced. Based on the equation of the generator \( f = \frac{N \cdot P}{120} \), it can be easily achieved by increasing either the rotation speed of the turbine (\( N \)), or pole number (\( P \)) in the generator (see Table I).

<table>
<thead>
<tr>
<th>Rotation speed</th>
<th>N=3600rpm</th>
<th>N=7200rpm</th>
<th>N=14400rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole number</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P=2</td>
<td>2500km</td>
<td>1250km</td>
<td>625km</td>
</tr>
<tr>
<td>P=6</td>
<td>833km</td>
<td>317km</td>
<td>158km</td>
</tr>
<tr>
<td>P=12</td>
<td>417km</td>
<td>208km</td>
<td>104km</td>
</tr>
</tbody>
</table>

To achieve variable frequency power transmission, a new transmission scheme is proposed, as depicted in Fig.1. According to the transmission line length, the remote power generator produces a corresponding frequency power, which is stepped up by the transformer, and then transmitted to the receiving end, where variable frequency power is changed to power frequency by frequency changer and supplied to the load centre.

The proposed transmission scheme is particularly designed for the non-network dedicated line, and is most effective and
economic for long distance, so its operation frequency does not need to be very high. Besides, frequency above 400Hz leads to some potential problems, like radiation and skin effect. Hence, the appropriate frequency range recommended by authors is from 60Hz to 300Hz (i.e. 500km-2500km).

III. FEASIBILITY STUDY

Feasibility study is carried out and three major components, power generator, transformer and frequency changer are studied.

A. Power Generator

Not like the steam turbine in conventional power generator, the rotation speed of industrial steam turbine is flexible, and its maximum value can reach 7000-12000 rpm, even 20000 rpm. For example, steam turbine SST-600 produced by Siemens has a speed range varying from 3000 to 18000 rpm, and has been widely used for generation [3]. Hence, variable frequency power generation is easy to implement.

On the other hand, rotating at appropriate high speed leads to two potential benefits [4]: i) optimized efficiency and gearbox-free. Each steam turbine has its optimum rotation speed, at which speed the efficiency is highest. Normally, this speed is higher than the generator’s speed. When facing this problem, one choice is to ignore it, so some thermal generators directly connect the turbine and generator, while another choice is to use a gearbox to decouple the turbine and generator, which brings some side effects like extra energy loss and additional cooling system requirement. The proposed transmission scheme provides the third solution, which is also the best. With higher power frequency, the turbine could naturally rotate at its optimum speed, or at least being closer to that speed, hence the efficiency is optimized without the help of the gearbox; ii) cost-effective and space-saving. The power developed at the turbine shaft is a function of the torque developed at the turbine blades and its rotation speed. If the turbine speed is increased, then a smaller diameter turbine would be required to maintain the same power, thus reducing the cost and size.

As for the hydro power unit, its rotation speed is normally very low and pole number is large, hence it is more appropriate to be used in the opposite situation, when the required transmission distance is longer than the natural HWTL length.

B. Transformer

A new transformer should be customized for the proposed scheme. As flux is inversely proportional to frequency, higher the frequency, less the flux required, thus leading to smaller size and weight. However, eddy current and hysteresis loss would be slightly higher due to higher frequency. To improve the performance, some newly-developed amorphous materials [5-6] could be considered.

C. Frequency changer

The frequency changer is the key equipment in the proposed scheme. Cycloconverter is the most economic option and it fits for large-power, frequency step-down applications. Power quality is the main concern, so multi-pulse is preferred and harmonic filter should be installed. Matrix converter, which is the derivation of the traditional cycloconverter, has better performance, but until now only achieved low penetration in large power application due to its complex control strategy and lower reliability.

Another option is AC-DC-AC converter, and the specific topology proposed by authors is shown as Fig. 2. Instead of using fully controlled rectifiers, 12 pulse diode rectifiers are used at stage 1 because: i) reactive power compensation is not required for the transmission line side, which is the key advantage of HWTL technology; ii) the power factor at the transmission line side is always close to one. If the HWTL is delivering power at unity power factor, the variation of voltage and current along the line is minimum[7]; iii) The cost is low, and no control strategy is required. As it is a current source inverter, the reliability is higher because the large inductor in DC link provides excellent short circuit and fault protection.

IV. CONCLUSION

A new transmission scheme – variable frequency half-wavelength transmission scheme, has been presented, which overcomes the distance problem existing in natural HWTL. The proposed scheme is most effective for long distance transmission, and particularly designed for the non-network dedicated line

REFERENCES


High Frequency Half-Wavelength Power Transmission Scheme

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Abstract—The half-wavelength power transmission scheme has some unique advantages and disadvantages for power transmission. This letter presents a new method to take advantage of the scheme and to overcome its main difficulty. The idea is to create a high frequency generation-transmission system as one unit. Feasibility of the proposed scheme is discussed.

Index Terms—Power transmission technology, frequency changer, half-wavelength transmission, high frequency power generator.

I. INTRODUCTION

Half-wavelength transmission line (HWTL) means that the line length between the sending and receiving ends is about half of the wavelength of the AC current carried by the line. Power transmission at this distance has one very attractive feature: the total line impedance becomes virtually zero (for lossless line). As a result, the sending end can be considered as just at the receiving end [1].

At 60Hz frequency, the half-wavelength is 2500km and is a fixed length, which is too long and inflexible for practical use. Solutions proposed to solve this problem in the past include the use of artificial lines made of Pi tuning, T tuning, and capacitor tuning circuits. These components bring new problems, such as overvoltage at the capacitor banks, in addition to increased cost [2].

With the advancement of power electronic technology, it has become economical to change power frequency. This makes it possible to change the half-wavelength. However, this idea alone is not enough to make the HWTL scheme competitive with schemes such as the HVDC. This paper proposes to generate power directly at higher frequencies, thus creating a single generator-HWTL unit. This idea will save one terminal for frequency conversion and has some other major advantages. It is specially conceived for cases where a large amount of power needs to be transmitted from a remote location to a load center.

II. PROPOSED SCHEME

A high voltage line can be approximated as a lossless line for transmission capacity studies. For a lossless line, the voltage and current at distance \( x \) from the sending end can be determined as follows:

\[
\begin{bmatrix}
U \\
I
\end{bmatrix} =
\begin{bmatrix}
\cos\alpha & -jZ_c\sin\alpha \\
-j\sin\alpha/Z_c & \cos\alpha
\end{bmatrix}
\begin{bmatrix}
U_s \\
I_s
\end{bmatrix}
\]

where \( Z_c \) is the surge impedance of the line and \( \alpha \) is the phase constant, \( \alpha = 2\pi/\lambda \) (\( \lambda \) is wavelength). If \( x = \lambda/2 \), equation (1) becomes

\[
\begin{bmatrix}
U \\
I
\end{bmatrix} =
\begin{bmatrix}
-1 & 0 \\
0 & -1
\end{bmatrix}
\begin{bmatrix}
U_s \\
I_s
\end{bmatrix}
\]

(2)

The above equation implies that there is zero impedance between the sending and receiving end of the line, as if the line did not exist. The line only changes the phase of the voltage and current.

As aforementioned, the main drawback of HWTL at 60Hz is its excessive and fixed length. To overcome this problem, one solution is to change the frequency of the carrier voltage. The electrical wavelength is related to the frequency of carrier voltage by \( \lambda = v/f \), where \( v \) is the wave propagation speed which is close to \( 3 \times 10^8 \) m/s, and \( f \) is the frequency of the voltage. If the frequency is raised, the corresponding length of HWTL can be reduced.

This letter further proposes to use high-frequency generators to produce a required frequency that leads to a half-wave length matching the distance between the generator and the receiving end, as shown in Fig. 1. In this scheme, the generator and the line are designed and constructed as one unit that just works for the required transmission distance.

![High frequency half-wavelength transmission scheme](image)

Fig. 1. High frequency half-wavelength transmission scheme.

It is clear that the proposed scheme is not suitable for networked operation. Its intention is to bring a large remote generator closer to the load center using HWTL. For example, a nuclear plant can be built at a remote location for safety purposes. But electrically speaking, the generating plant is located at the load center with the help of HWTL scheme.

According to the relationship between the generator speed \( (N_g) \) and pole number \( (P) \), \( f = N_g \times P/120 \), sample combinations of \( N_g \) and \( P \) to produce various half-wave length is shown in Table I. Note that the frequency recommended is less than 400Hz, as very high frequency may create other unforeseen issues in transmission line design.
The proposed scheme does need one frequency changer at the receiving end. Since there is only one frequency changer needed, the scheme becomes more competitive in comparison with the HVDC scheme. Other technical feasibility considerations for the proposed scheme are discussed next.

III. FEASIBILITY ANALYSIS

Feasibility study is carried out for the proposed scheme, especially for its three major components: generator, transformer and frequency changer.

A. Generator

The rotation speed of industrial steam turbine is quite flexible and can be as high as 20000 rpm. For example, steam turbine SST-600 produced by Siemens has a speed range varying from 3000 to 18000 rpm, and has been widely used for power generation [3]. Hence, high frequency power generation is easy to implement.

In fact, running a turbine at a higher speed has two additional benefits: i) Higher efficiency and lower cost. Each steam turbine has its optimal rotation speed where the efficiency is the highest [4]. Normally, this speed is higher than the generator’s speed. Existing solution to deal with this problem is to use gearbox, which causes extra energy loss and requires cooling system. The proposed transmission scheme can increase the generator speed and hence the efficiency could be optimized without using gearbox; ii) Space-saving. The power developed at the turbine shaft is a function of the torque developed at the turbine blades and its rotation speed [5]. If the turbine speed is increased, then a smaller diameter turbine would be required to maintain the same power, thus reducing the cost and size.

As for a hydro power unit, its rotation speed can also be increased through hydraulic design. Increasing pole numbers may not be an option since hydro generators have many poles already.

B. Transformer

Two custom-made high frequency transformers are needed for the scheme. As flux is inversely proportional to frequency, higher frequency requires less flux. It will lead to smaller size and weight for the transformer. The eddy current and hysteresis loss could be slightly higher. To improve the performance, some newly-developed amorphous materials [6-7] may be considered. Note that high voltage transformers are always custom made even at 60Hz. So the proposed scheme does not add a lot of work for transformer procurement.

C. Frequency changer

The frequency changer is the key equipment in the proposed scheme. Cycloconverter is the most economic option and it fits for large-power, frequency step-down applications. Power quality is the main concern for the frequency changer. More research can be done in this topic, such as multi-pulse cycloconverter, matrix converter, and novel harmonic filters.

Another option is the AC-DC-AC converter. The specific topology proposed here is shown as Fig. 2. Instead of using fully controlled rectifiers, 12 pulse diode rectifiers are used at the high frequency side, just like the traditional current-source variable frequency drive. Since the generator is “located” electrically at the receiving side, reactive power compensation is not required and power factor can be controlled by the generator to close to one. The control is simpler too. As it is a current source inverter, the reliability is higher because the large inductor in the DC link provides excellent short circuit and fault protection.

IV. CONCLUSION

A new transmission scheme – high frequency power generation and half-wavelength power transmission in one unit - has been proposed in this letter. The scheme is not affected by the distance between the generator and load center. Preliminary feasibility analysis indicates the scheme is highly feasible and it has additional advantages. More research work is needed to develop an efficient frequency changer that is customized for the scheme.

References