

Inverter Frequency and Transformer for Low Frequency Power Transmission

Atsushi Nakata⁽¹⁾, Akihiro Torii⁽²⁾, Akiteru Ueda⁽²⁾
Shizuoka Institute of Science and Technology⁽¹⁾, Aichi Institute of Technology⁽²⁾
a-nakata@ee.sist.ac.jp, tori@aitech.ac.jp, aueda@aitech.ac.jp

Abstract

In this paper, we examine inverter frequency and transformer for low frequency power transmission, and report the simulation results.

1. Introduction

Japan has a huge exclusive economic zone, and the electricity generated from renewable sources in offshore areas should be transmitted to power consumption areas efficiently.

A high voltage direct current transmission (HVDC) is commonly used for long distance transmissions. It has two advantages.

(1) The voltage drop according to transmission frequency is theoretically zero, since the frequency of the HVDC is zero.

(2) DC systems can use the maximum allowable voltage of cables, although the root mean square value (rms) voltage of an alternating current system is usually smaller than the maximum allowable voltage of the cable. In HVDC, a large capacitor used for reactive power compensation is needed, since the power factor in a thyristor converter is low. In addition to the capacitor described above, filters which eliminate harmonic currents generated by the thyristor converter are needed. The thyristor converter needs a large inductor for continuing the dc current in the case of a small dc current. There is no zero cross point of current. It is therefore very difficult for a high speed DC circuit breaker to cut an electric arc.

In AC transmission systems, cross linked polyvinyl (CV – Also known as XLPE) cables are commonly used as power cables with cross linked polyethylene, and polyvinyl chloride (PVC) sheaths. The AC-CV cables are cheap and cost effective. They are used in a variety of applications including power transmission, power distribution and wiring systems. However, when a DC voltage is applied to the AC-CV cables, an electric breakdown occurs by space charges accumulated in insulators [1]. Therefore, oil-filled cables (OF cable) or mineral insulated DC-CV cables insulated by a XLPE compound containing inorganic filler [2] are used. However, both of these solutions are expensive to implement.

The power transmission in the frequency of 5 Hz to 10Hz using AC-CV cables is proposed [1]. In this paper, we examine inverter frequency and transformer for low frequency power transmission, and report the simulation results.

2. Long distance transmission

<2.1> HVDC system

Fig.1 shows a simplified model of Kii-channel high voltage DC system [3]. Phase modifying equipment including power factor correction capacitors, transformers of the converter equipment, thyristor converters, harmonic current filters and DC inductors are installed in the HVDC substation. In the phase modifying equipment whose DC power capacity is 1400 MVA (100%), the power factor correction capacitor in a thyristor rectifier is 480 MVA (34.3%) and that in a thyristor inverter is 720 MVA (51.4%). Generally, it is said that the thyristor rectifier side needs 30%-50% and the thyristor inverter side needs 40%-60% of the power factor correction capacitor [4]. These costs are a matter of money.

Generally, these values agree with experimentally implemented values: the capacity of the thyristor rectifier side is 30%-50% of the power factor correction capacitor and that of the thyristor inverter side is 40%-60%. The use of these capacitors requires additional expenses.

A transformer of converter equipment uses a three-winding type. Although this transformer does not show details, the primary side is a Y-connection and the secondary side is a delta-connection in the transformer. Therefore, the thyristor converter is 12-pulse, and harmonic currents of 11, 13, 23 and 25 orders are generated by the converter theoretically.

However, uncharacteristic harmonics are generated, because of unbalance phase-control angle in the thyristor converter and impedance dispersion of a respective phase in the power system.

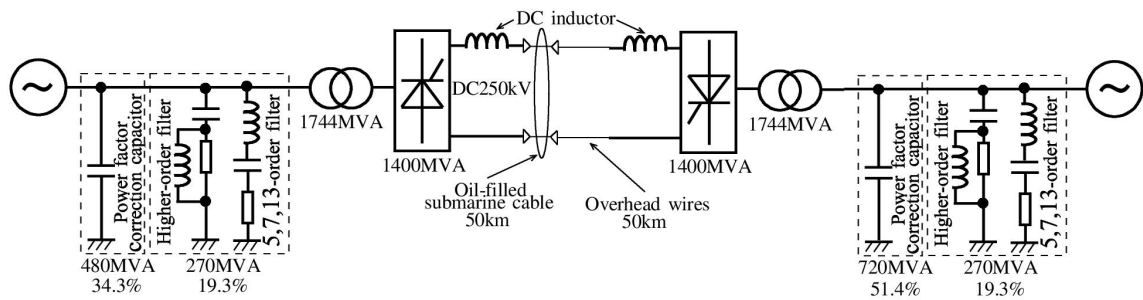


Fig.1. Simple model of Kii-channel high voltage DC system.

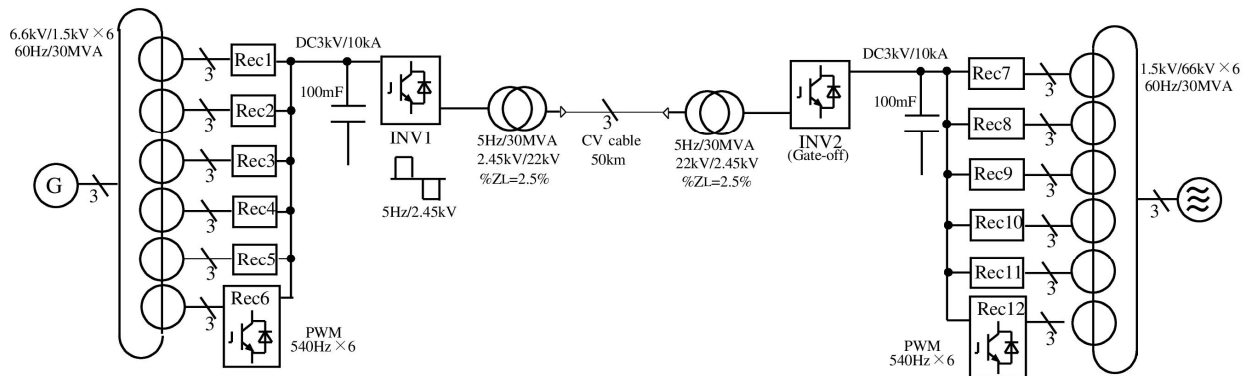


Fig.2. Proposed system configuration.

The currents which are generated by the thyristor converter contain a lot of harmonic currents. Since the harmonic currents cause the heating of adjacent equipment and the inductive interference of adjacent communication lines, harmonic current eliminating filters are used. This capacity of the filter is 270MVA in the rectifier and inverter [3]. This is 19.3% with respect to the converter capacity. The cost of the filter is a problem.

In the HVDC, the DC inductor is inserted in the thyristor rectifier and inverter DC side. The purposes of the DC inductor are;

- (1) Obtaining a smooth current by attenuating ripples.
- (2) Preventing an intermittent current in the case of a small current.
- (3) Preventing an over-current in the case of a power failure.

For these reasons, the large inductance DC inductor is needed. Since the DC current does not have a zero point, the DC circuit breaker for a large current is needed. These costs are also problems.

<2.2> Low frequency power transmission system

Fig.2 shows the proposed system configuration. This system can interchange the 30MVA power bidirectionally. However, the power flow is shown from left to right in order to simplify the explanation in Fig.2. The 60Hz transformer is six open-winding, and the respective output voltage is 1.5kV. We are assuming that the inductance component is 10% and the winding resistance component is 1% in the short-circuit impedance of the transformer. The parallel connection IGBTs of 4.5kV are used in the PWM rectifier Rec1-12. The triangle carriers of the series multi-winding PWM rectifier are 540Hz and shifted by 60° respectively. The Rec1-6 are controlled in constant 3kV DC voltage. The Rec7-12 controls a utility connected operation. Since these converters are six series multi-winding inverter, the equivalent switching frequency becomes 3.24 kHz. Therefore, the harmonic current eliminating filter is not needed in the primary side of the transformer.

The parallel connection IGBTs of 4.5kV

are also used in the PWM inverter of INV1 and 2. The INV1 is used as a 120 degree square-wave inverter, (5Hz and 3kV peak). Since the INV2 is gate-off, it operates as a diode rectifier. By using square-wave alternating current power transmission [5], the transformer can boost the maximum insulation voltage of the cable.

We assumed that the characteristics of the CV cable to have a wiring resistance of zero, an inductance of 350 μ H/km, a line-to-line capacitance of 0.3 μ F/km and a cable length of 50km. It is known that space charge formation in insulator of the CV cable is neutralized by the AC voltage 1Hz or over [1]. Therefore, the frequency of the inverter has to be 1Hz and over. Moreover, Funai and Matsuura reported that a long distance transmission of several hundred kilometers using the cable which is much the same as HVDC [1].

3. Design for proposed system

<3.1> Output frequency and voltage

The cable impedance is ZL and the cable admittance is YC in the case of 5Hz and 10Hz. The respective percent impedance and percent admittance are shown in Table.1. When a rated current flows through the 50km cable, the voltage drops from the cable impedance are 3.41% and 6.82% in the case of 5Hz and 10Hz. We decide that the inverter frequency should be 5Hz, considering that a reactive power and a voltage fluctuation suppression. Also, the system voltage should be 22kV since the cable can be considered as an LC filter.

<3.2> Transformer

We examine the design of the low frequency transformer. The design examples are shown in Table.2. These design values are determined by a permeance method [6]. Here, the maximum value of the magnetic flux density B is 1.5T, the effective sectional area of the iron core is 0.9, the standard magnetic loading is 0.03, and the three-leg iron core is used. The turn ratio of the transformer and the sectional area ratio of the iron core are the square root

of the frequency ratio which is $\sqrt{60/5}=3.464$.

The short circuit impedance is about 15% in the general extra-high voltage transformer which is 22kV-3.3kV, 30MVA, 50Hz, etc. It is estimated that a leakage inductance %zL of low frequency 5Hz transformer is about 1.5%. This transformer has to take measures to prevent bias magnetism using inverters. Supposing that gaps are formed, the leakage inductance %zL is 2.5%.

The low frequency power transmission system can use a low cost CV cable. The system does not need a DC inductor, a harmonic current eliminating filter or a power factor correction capacitor. Therefore, it is considered that the cost of the increasing the size of the low frequency transformer is neutralized.

Table 1. %ZL and %YC of CV cable in 30MVA system.

System voltage [kV]	Rated current [A]	5Hz		10Hz	
		%ZL [%]	%YC [%]	%ZL [%]	%YC [%]
22	787.3	3.41	2.28	6.82	4.56
33	524.9	1.51	5.13	3.03	10.26
66	262.4	0.38	20.53	0.76	41.05
110	157.5	0.14	57.02	0.27	114.04
154	112.5	0.07	111.76	0.14	223.52
220	78.7	0.03	228.08	0.07	456.16

Table 2. Design of low frequency transformer.

Frequency [Hz]	Maximum Magnetic flux [Wb]	22kV side winding [Turn]	2.45kV side winding [Turn]	Iron core sectional area [m ²]
60	0.387	213	24	0.287
5	1.342	739	82	0.994

4. Simulation

In the simulation, we examine the low frequency inverter, cable equivalence circuit, and receiving voltage side diode rectifier. A simulation circuit is shown in Fig.3. A block diagram of inverter control is shown in Fig.4. The voltage vibration suppression is controlled by detecting an inverter output current in Fig.4.

The INV1 uses an over amplitude modulation control since a switching of the inverter is done at a zero cross point of an output voltage. The inverter voltage can output mixed voltages which are a square wave voltage and a PWM wave voltage by using the over amplitude modulation control.

Fig.5 shows the inverter output voltage

VINV, the receiving end voltage V_{end} , the cable current I , and the DC voltage V_{dc} in the simulation results. The cable current I flows to 872.5 Arms in comparison with the rated current 787.3 Arms. The cable current is about 10% more than the rated current because the receiving side has a diode rectifier. These are caused by low harmonic currents and leading currents for line capacitances.

The rise and fall of PWM around zero cross can suppress the voltage vibration, and the received voltage can be a trapezoid wave. The stable DC voltage can be received at the receiving end.

5. Conclusion

In this paper, we examine the inverter frequency and transformers for low frequency power transmission, and report simulation results by design value. We consider the cable as LC filter, and control the voltage vibration suppression by an LC resonant.

By using the over amplitude modulation control and the voltage vibration suppression control, the received voltage can be a trapezoid wave. We reveal a sufficient electric power transfer capability which uses 50km CV cable.

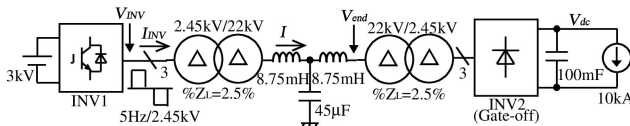


Fig.3. Simulation circuit.

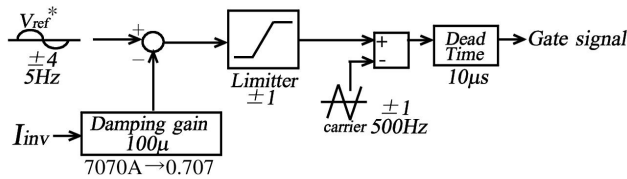
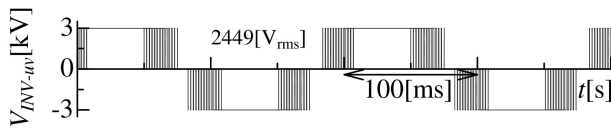
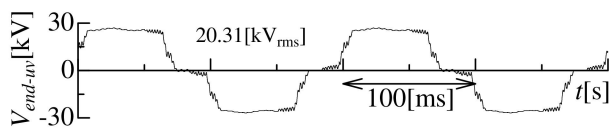


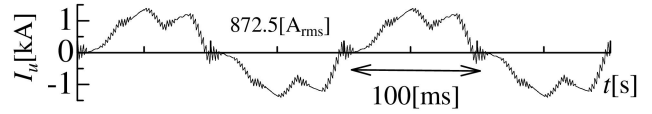
Fig.4. Block diagram of inverter control.



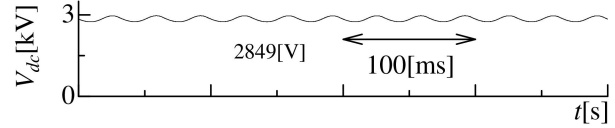
(a) Inverter output voltage waveform



(b) Receiving-end voltage waveform.



(c) Cable current waveform.



(d) DC voltage waveform.

Fig.5. Voltage and current waveforms.

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