The three-level inverter topologies analysis for application by electric centrifugal pump units

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Abstract. In the article, the schemes for providing AC power with frequency conversion for the induction submersible electric drive of oil production units are analyzed. The electric submersible drive is widely used and has stringent efficiency requirements, so this research is relevant. The centrifugal pump units are composed of a low-voltage power source, a frequency converter, a step-up transformer, a cable line, an electric drive and a centrifugal pump. This article discusses options for replacing the step-up transformer and two-level voltage / frequency converter with a three-level flying capacitor converter (FCC) or a three-level clamping diode converter (NPC). The expected states of the power high voltage IGBT modules are described. The waveforms of the inverter output voltage and the submersible induction motor stator voltage in different circuits are shown. A voltage levels analysis for each module is done, the electric drive starting time change is estimated, the total harmonic distortions (THD) are calculated, and a 1.1% THD reduction by applying the NPC circuit is shown. The harmonic current spectrum for each circuit is presented.

1. Introduction

Submersible electric centrifugal pumps (ESP) perform artificial lift of oil from the main types of wells. This solution is widely used, therefore, the issue of the ESP efficiency increasing is relevant. ESP equipment includes a centrifugal pump with a gas separator, an oil-filled induction motor, a submersible cable line, a transformer and a control station [1,2].

The control station supply voltage is 0.4 kV with a frequency of 50 Hz. The control station adjusts the output voltage frequency for the submersible motor to control the pump speed. The step-up transformer increases the voltage to 1-3 kV to reduce the electrical power losses in the submersible electric motor power circuit.

The oil well cluster is powered by a 6 kV line through a 6/0.4 kV step-down transformer. Thus, the voltage level is converted twice. Each transformation stage increases the power losses in the electrical circuit.

The control station includes a power converter, which consists of a rectifier, a filter, and a three-phase bridge two-level inverter. To reduce the total harmonic distortions (THD), it is proposed to use three-level inverters connected to the general rectifier output at a 6 kV voltage of the oil well cluster power system [3,4].

2. Three-level voltage inverter circuit with flying capacitors.

The flying capacitor circuit (FCC) is one of the three-phase three-level inverter topologies. A circuit with a capacitive voltage divider is proposed (Figure 1). The divider reduces the voltage across the power semiconductor transistors to acceptable values and simultaneously provides electrical power to three wells. This circuit, in contrast to the circuit with a two-level inverter, allows obtaining additional
voltage values $+\frac{U_d}{2}$ and $-\frac{U_d}{2}$. The circuit includes a 6kV oil well cluster main rectifier (DR), a capacitive voltage divider and three three-level voltage inverters (MLI). The inverters are connected to a submersible motor (M) with a cable line (L). The voltage divider at the main rectifier output reduces the voltage at the inverter input to an average value (1):

$$U_d = \frac{U_{DR}}{3} = \frac{6000}{3} = 2000 \text{ V}$$

(1)

This value corresponds to the HV winding rated voltage of the TMPN63000 step-up transformer (1980 V).

Also, a three-level inverter topology reduces the maximum applied reverse voltage per IGBT-module in half compared to a two-level inverter circuit (2).

$$U_{revIGBT} = \frac{U_d \sqrt{2}}{2} = \frac{2000\sqrt{2}}{2} = 1414.21 \text{ V}$$

(2)

This voltage level is acceptable for modern high voltage IGBT-modules.

Four power switches VTx1, VTx2, VTx3, VTx4 are connected in series in one arm of the inverter. The central power switches are enclosed by capacitors. These capacitors are called «flying capacitors» [5-7] because they pass voltage in the forward and reverse directions.

![Diagram of three-level voltage inverter circuit with flying capacitors.](image)

When the external power switch VTx1 or VTx4 is turned on, the capacitor is charged to half the power supply voltage. When a pair of upper or lower keys are closed, the output voltage will be either $U_d$ or $-U_d$, respectively. Two intermediate states are achieved when the transistors VTx1 and VTx3 or VTx2 and VTx4 are closed. Then the voltage will be respectively $\frac{U_d}{2}$ or $-\frac{U_d}{2}$ (Table 1). One of this circuit disadvantages is the need for a $du/dt$ voltage filter at the converter output. This creates additional power losses. It is also necessary to balance the capacitors voltage.
Phase Shifted Pulse Width Modulation (PS-PWM) method is applied to control power switches.

### Table 1. Flying capacitor inverter state table

|   | VTx1 | VTx2 | VTx3 | VTx4 | $U$ | $U_{C1}$ dynamics |
|---|------|------|------|------|-----|------------------|
| 1 | 1    | 1    | 0    | 0    | $U_d$| up               |
| 2 | 1    | 0    | 1    | 0    | $U_d/2$| down            |
| 3 | 0    | 1    | 0    | 1    | $-U_d/2$| down            |
| 4 | 0    | 0    | 1    | 1    | $-U_d$| up              |
| 5 | 0    | 0    | 0    | 0    | 0    | -                |

3. Three-level voltage inverter circuit with clamping diodes

A three-level clamping diode inverter circuit (NPC) is an alternative to a FCC with the same number of power switches per phase (Figure 2).

![Figure 2. Three-level voltage inverter circuit with clamping diodes](image)

This inverter, in comparison with a two-level inverter, can reduce harmonic distortions. This allows to reduce the filters size and increase the electric drive efficiency. In the circuit, in addition to four IGBT-modules with anti-parallel diodes, two clamping diodes are connected in each phase [8-10]. Diodes connect the capacitive divider midpoint to the midpoints of the cathode and anode arms.

In the operating mode, the circuit allows obtaining five values of the output voltage: $U_d; U_d/2; 0; -U_d/2; -U_d$, which are provided by twenty possible states of the keys (Table 2). It should be noted...
that the simultaneous opening pulses supply to all four transistors of the bridge rack is unacceptable. In this case, there will be a short circuit.

**Table 2. Clamping diodes inverter state table**

|   | VTx1 | VTx2 | VTx3 | VTx4 | U   |
|---|------|------|------|------|-----|
| 1 | 1    | 1    | 0    | 0    | U_d |
| 2 | 0    | 1    | 0    | 0    | U_d/2|
| 3 | 0    | 0    | 1    | 0    | -U_d/2|
| 4 | 0    | 0    | 1    | 1    | -U_d |
| 5 | 0    | 0    | 0    | 0    | 0   |

4. **Numerical simulation**

To assess the use of three-level FCC and NPC inverters in centrifugal pump units, simulation models in the Matlab environment have been developed. Comparison of simulation results with a two-level inverter and a step-down transformer is performed. The simulation model includes a three-level voltage inverter (FCC), a constant voltage source (DC), an IGBT module control unit (PWM), a cable line (W), a submersible induction motor (Submersible motor), a mechanical load unit (Load). The system operation was investigated in starting modes. Submersible motor power is 63 kW, rated voltage is 1980 V, cable length is 1150 m.

![Figure 3](image-url)

**Figure 3.** The inverter output voltage time plot: T – a circuit with a step-up transformer, NPC – a circuit with a three-level clamping diodes inverter, FCC – a circuit with a three-level flying capacitors inverter

Figure 3 shows the correspondence of the line voltage levels for the three inverters. The number of voltage levels affects the harmonic distortion.
Figure 4. The stator voltage time plot: T – a circuit with a step-up transformer, NPC – a circuit with a three-level clamping diodes inverter, FCC – a circuit with a three-level flying capacitors inverter.

Figure 5. The stator current time plot: T – a circuit with a step-up transformer, NPC – a circuit with a three-level clamping diodes inverter, FCC – a circuit with a three-level flying capacitors inverter.
Figure 6. The submersible electric motor rotor speed time plot: T – a circuit with a step-up transformer, NPC – a circuit with a three-level clamping diodes inverter, FCC – a circuit with a three-level flying capacitors inverter.

To analyze the harmonic composition, load current spectrograms are presented (Figure 7-9).
Figure 8. The current spectrogram a circuit with a three-level clamping diodes inverter.

Figure 9. The current spectrogram a circuit with a three-level flying capacitors inverter.
5. Conclusion
The power supply of electric centrifugal pump units of cluster oil fields with the main rectifier and three-level inverters has the following advantages:
– absence of a step-down transformer and a step-up transformer as a additional power losses source;
– lower overvoltage level in NPC and FCC circuits compared to a two-level inverter and step-up transformer circuit (Figure 4);
– the electric motor starting time in circuits with a three-level inverter is almost two times less (Figure 5-6), since the electromechanical time constant of the NPC inverter is 1.9 times less;
– current harmonic distortion is reduced (Figure 7-9), THD for a circuit with three-level clamping diodes inverter is 6.87%, while for a circuit with a step-up transformer 7.97% and 17.16 for a circuit with a three-level flying capacitors inverter. Low-frequency harmonics are typical for a traditional circuit with a two-level inverter. More powerful filters are required to suppress these harmonics.
However, NPC and FCC schemes have several disadvantages:
– more difficult power switch control;
– a larger number of power switches reduces the reliability of the entire system;
– the use of high-voltage semiconductor modules instead of low-voltage IGBT modules.
In addition, the disadvantage of the FCC circuit is the need to balance the capacitors voltage.

6. References
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