Inductive Power Supply for On-line Monitoring Device

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Abstract. The development of power supply technology is the key to improve the on-line monitoring device which ensures the reliability and intelligence of power grid. In this paper, a design scheme of inductive power supply for on-line monitoring device is proposed. The AC/DC converter circuit without rectifier bridge and the black-start circuit are designed. The control module uses the backup battery to solve the problem of insufficient power supply and control strategy adopts the principle of MPPT. The validity of scheme is verified by testing the prototype. Test results shows that prototype can not only work in a wide current range of line current and load but also work at maximum power point and change the working mode following the change of load and line current.

1. Introduction
The development of smart grid requires on-line monitoring devices to be more intelligent and perfect to ensure the high reliability of power grid. However, the power supply for on-line monitoring devices still has many limitations need to improve. For example, the operating current of the Power Donut (on-line monitoring device manufactured by USI) is higher than 50A, while the load current of 110kV transmission line may appear as low as 20A which would cause the device to not work properly. Besides, some devices have sampling rate limitation due to the limitation of power supply. On the other hand, the weight of the on-line monitoring devices also need to be strictly controlled for the sake of line safety which means the energy density of the power supply should be increased to minimize the weight of the on-line monitoring devices.

The power source option of on-line monitoring devices include magnetic fields, electric fields, solar energy and wind energy. The inductive power supply [1-3] based on current transformer is the best choice considering the cost, which is of small size, low cost and easy to install so that it has been widely applied.

In this paper, a design scheme of inductive power supply for online monitoring device is proposed, which consists of electrical transformer [4-5], rectifier module, control module and backup battery. The efficiency of electrical transformer is improved by using high energy density magnetic core. The rectifier module adopts AC/DC circuit without rectifier bridge to reduces the loss caused by the rectifier bridge and black-start circuit which could activate the power supply system when the line current is very low. The control module adopts the FSM (Finite State Machine) control mode which ensure the system output stable voltage no matter how the line current changes and MPPT (Maximum Power Point Tracking) control strategy which could track the maximum power point of the magnetic core to improve the energy density of output power. The backup battery ensures the on-line monitoring devices work properly when line current is small even zero and charge itself when line current is large.
The inductive power supply designed in this paper can change working mode with the change of line current so that it can supply stable power to on-line monitoring device. This inductive power supply can solve the problem of power supply for on-line monitoring device, which can further improve the reliability of smart grid.

2. Hardware Design of Inductive Power Supply System

The block diagram of inductive power supply system is shown in Figure 1 including transmission line, power coil, rectifier module, control module and load. This system acquires induced current through power coil and raises the voltage above the forward threshold voltage of rectifier transistor through transformer. Then the rectifier circuit which is controlled by DC bias produced by an astable multivibrator output DC voltage to DC/DC circuit. The DC/DC circuit consists of two parts. The first part converts the DC voltage output by rectifier circuit to 5V required for lithium battery charging. The second part converts the voltage to 3.3V required for load. Charge and discharge of lithium battery is controlled by the voltage signal from the secondary side of transformer and the current signal from transmission line, which are both input into MCU and MPPT circuit. Backup battery can supply power to load when power coil cannot get enough energy from line or load increase unexpected.

\[ E_2 = \sqrt{2\pi f N_2 \Phi_m} \]  

Where \( N_2 \) is the turns number of secondary side and \( \Phi_m \) is the max main flux. According to the magnetomotive balance equation of the transformer:

\[ I_1 N_1 + I_2 N_2 = I_m N_1 \]  

Where \( N_1 \) is 1, \( I_2 \) is the secondary side current, \( I_m \) is excitation current. The magnetization current \( I_\mu \) is equal to excitation current \( I_m \) when load is resistive and ignoring the two side internal resistance and iron consumption. Therefore, the relation between the magnetizing current, primary side current and secondary side current is:

\[ I_\mu = \sqrt{I_1^2 - (N_2 I_2)^2} \]  

The maximum main flux \( \Phi_m = B_n S \), where \( S \) is the sectional area of power coil. The magnetic

![Figure 1 block diagram of inductive power supply system](image)
induction $b_n = \mu H_n$, where $H_n = \sqrt{2} N I_\mu / l$ according to Ampere's law. $l$ is average length of magnetic path. Therefore, the output power of secondary side is:

$$P_2 = E_2 I_2 = 2\pi f \mu I_\mu S \sqrt{I_1^2 - I_\mu^2} / l$$

Let $I_\mu$ be the independent variable and take a derivative of (6) with $I_\mu$. The maximum output power is shown in equation (5) when $I_\mu = \sqrt{2} I_1$:

$$P_{max} = \pi f \mu SI_1^2 / l$$

According to the characteristics of output power, the relationship between the size and the material of the core can be studied. It is also possible to study the maximum power control strategies to achieve higher energy density.

2.2. Design Scheme of Rectifier Circuit and Black-start circuit

The schematic diagram of the rectifier module after power coli is shown in Figure 2.

![Figure 2 Schematic diagram of the rectifier module](image)

The induced current in power coil is above the forward threshold voltage of rectifier transistor after raised up by transformer, but the boosting capacity is limited by the withstand voltage and the design of the electromagnetic core. That’s why there is an AC/DC circuit consisting of MOSFET and diode to boost the voltage again. Rectification is divided into four processes: charging, discharging, charging and discharging in a cycle. In the current path of charging and discharging, the inductance of the power coil and the leakage inductance of the transformer are used as energy storage elements which is charged when MOS is on and discharged when MOS is off. The output of the rectifier circuit is connected to an astable multivibrator which generates DC bias as the firing pulse by positive feedback to accomplish black-start. The voltage regulator tube maintain voltage within the safe operating range of the MOSFET to keep the stability of system. The capacitor is used for filtering and zener diode is for stabilizing the output voltage.

The AC/DC part is more efficient and with lower loss without the rectifier bridge. Besides, the complexity of power management circuits is reduced by using the inductance of the energy core and the leakage inductance of the transformer as energy storage elements rather than another inductor.

The schematic diagram of the black-start circuit is shown in Figure 3, which is an astable multivibrator. The input of oscillator is the DC output of AC/DC circuit and the output of black-start circuit is connected MOS through a resistor. The astable multivibrator can generate DC bias by positive feedback to control the on-off state of push-pull circuit when input voltage is very low. The duty cycle is controlled by controlling the ratio of the resistance and capacitance which guarantees the constant DC voltage output of rectifier module.
2.3. Design Scheme of Control Module

There is a positive correlation between the power supplied by the coil and the line current so that the on-line monitoring devices won’t work properly when line current is low. The black-start circuit solve the problem that rectifier module couldn’t work without firing pulse when restoration after power failure. While the system still cannot work continuously in case of no-load and light-load which makes the backup battery necessary. The on-off state of the switch is controlled by control module with certain management strategy which is depends on the voltage and current signals of the front circuit. The backup battery is charged through PWM control when line current is large or supply to load when rectifier module cannot afford sufficient power. The block diagram of the control module is shown in Figure 4.

3. Control Strategy of Inductive Power Supply System

The control strategy of inductive power supply system is FSM and MPPT which is implemented by MCU. FSM specifies a time step in advance, then executes instructions and output control signals according to the current and voltage of key point. The control signal remains unchanged until next time step. The power supply system has three operating modes, which are normal operation mode, charging mode and auxiliary power supply mode. The power coil get energy from transmission line to
supply power to load and lithium battery acts as backup power when line current is appropriate. The power coil supply power to load and charge the battery when line current is large enough. The battery supply power to load when line current is too low or load is too heavy that power coil cannot supply enough power. The switching criterion between each mode is mainly based on line current, still the maximum and minimum values of the battery voltage should be taken into consideration.

The battery can supply power to load when system startup, which ensure the load get enough start power. Then the control module will check the working status of the system to determine which operating mode should the system be. The switch between three operating modes is shown as Figure 5.

3.1. Design Scheme of MPPT Circuit
MPPT control refers to the dynamic control of the output power of power coil when the primary side current is small, so that it always operates at the maximum power point. The size and weight of the power coil is reduced by this control strategy.

We can conclude that the output power of the power coil will reach to the maximum when
\[ I_m = \frac{\sqrt{2}}{2} I_1. \]

Then the magnetizing current \( I_m \), output current \( I_{sec} \) and output voltage \( V_{sec\text{pmax}} \) may be expressed as follows:

\[ I_{sec} = I_{m} \quad (6) \]

\[ V_{sec\text{pmax}} = \frac{\sqrt{2} \pi f \mu N_s I_1}{l} \quad (7) \]

Therefore, the power coil will output maximum power when the output voltage is \( V_{sec\text{pmax}} \) as in (7) and lag the primary side current \( I_1 \) 45 degrees (assuming the load is resistive). The block diagram of MPPT is shown in Figure 6.

\[ V_{sec1} \] is the output of power coil after rectification and amplification. \( V_{ref} \) is the output of measuring coil after rectification, amplification and phase-shifting \( \phi \) degrees. Let \( V_{ref} \) is equal to \( V_{sec\text{pmax}} / K_i \) and lag the primary side current \( I_1 \) 45 degrees by setting the value of \( K_2 \) and \( \phi \). The comparator 1

![Figure 5 Operating modes switch](image)

![Figure 6 Block diagram of MPPT](image)
compares the value of $V_{ref}$ with $V_{sec}$ to control the state of MOS. The switch is on and battery supply power to load when $V_{ref} > V_{sec}$. The switch is off and is supplied by power coil when $V_{ref} < V_{sec}$. The output voltage of the coil can be adjusted by changing the duty cycle of the switch so that the $V_{sec}$ always follow $V_{ref}$ which means the power coil always outputs the maximum power. $V_{set}$ is the minimum voltage that enables the AC/DC circuit to work. The comparator 2 lock down the comparator 1 when $V_{ref} < V_{set}$ to turn on the switch so that the load is supplied by battery. Diodes ensure the battery and AC/DC circuit only supply power to load. The maximum power tracking circuit cooperates with the MCU to realize power management of the system.

3.2. Control Strategy of AC/DC circuit

The AC/DC circuit proposed by this paper adopts MOSFET and diode instead of rectifier bridge, which needs corresponding control strategy. Rectification is divided into four processes: charging, discharging, charging and discharging in a cycle which is shown in Figure 7. The inductance of the power coil and the leakage inductance of the transformer are used as energy storage elements. The inductance is charged when $0<ωt<\pi/2$ and MOS is on as shown in process I. The inductance is discharged and supply power to load when $\pi/2<ωt<\pi$ and MOS is off as shown in process II. The inductance is charged when $π<ωt<3\pi/2$ and MOS is on as shown in process III. Process IV is the same as process II that the inductance is discharged and supply power to load.

4. System Test and Result Analysis

A prototype of power supply system is developed and tested to verify the validity of design scheme proposed by this paper. The output power coil is tested when transmission line current is 5A, 10A, 15A and 20A. The result is shown in Figure 8.
Figure 8 Test result of output power

The result shows that the output power is nearly 600mW when line current is 10A. The output power of power supply system is even more than 300mW considering the loss of system which meets most of the power requirements of on-line monitoring devices.

The black-start and mode switching function of the power supply system is tested. The result shows that the system can work properly in a wide range of line current and load. Besides the system can maintain more than 75% power conversion efficiency in normal working mode. The prototype is shown in Figure 9.

Figure 9 Prototype of power supply system

5. Conclusion
This paper proposed a design scheme of inductive power supply including structure, hardware and control strategy. This paper studied the output characteristics of the power coil and MPPT control strategy to develop the global control strategy. Besides, this paper designed black-start circuit, backup battery and rectifier circuit without rectifier bridge. The test result shows that system can supply more than 300mW power when line current is 10A which meets most of the power requirements of on-line monitoring devices. The power supply can supply stable power when line current is very low which ensure the on-line monitoring device work properly when grid restore from power failure. Furthermore the control strategy ensure the power supply work at maximum power point and change the working mode following the change of load and line current.

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