Intelligent Control Method of Power Supply for Tundish Electromagnetic Induction Heating System

Xinxing Xiang, An Luo, and Yan Li

Abstract—An intelligent control method is proposed to improve the performance of power supply for tundish electromagnetic induction heating, which can adequately regulate the tundish temperature. The topology structure of power supply for tundish electromagnetic induction heating is presented, and its working principle is analyzed. The power supply consists of six power units, and each of them consists of a fore-stage three-phase rectifier and back-stage single-phase inverter. The feed-forward control DC voltage is used by three-phase rectifier to obtain the stable DC voltage supplied to the inverter. The cloud controller based intelligent temperature control algorithm is combined with the power feed-forward algorithm to obtain accurate tracking of the output current and constant temperature control of the tundish steel in the back-stage inverter. The simulation and experiment are performed to verify the accuracy and effectiveness of the proposed method.

Index Terms—Cloud control, electromagnetic induction heating, rectifier-inverter, tundish.

I. INTRODUCTION

RECENTLY, with the progress of power electronics and semi-conductor technology, the emergence of high-power and high-efficient frequency conversion has significantly promoted the development of induction heating technology for steel heating. The practice of continuous casting technology indicates that the constant temperature casting with low superheat plays an important role in improving the quality and stable operation of a slab [1]-[4]. The input current of power supply for the tundish electromagnetic induction heating is the medium of power transformation and affects the power quality of public grids. Currently, its output relates to the temperature control of the tundish. The power supply for tundish electromagnetic induction heating is important for the production of special steel products in the continuous casting process [5].

One of the most effective methods to improve productivity, solidification structure, and product quality corresponds to the control of the molten steel temperature of the tundish [6]-[8]. Therefore, more and more researchers focus on seeking an external heat source to compensate for the temperature drop of the steel water in the tundish, precisely control the optimal superheat, and keep the temperature of the steel water in the crystallizer stable. Therefore, various forms of power supply for electromagnetic induction heating system were developed in recent decades [9]-[13].

In [9], a topological structure of a low-loss voltage-type high-frequency series-load resonant inverter with an auxiliary switching capacitor unit was proposed. The conventional structure of power supply for tundish electromagnetic induction heating consists of a rectifier and series-resonant multi-inverter [14]. In [15], a simple D-class inverter with constant frequency was proposed for high-frequency induction heating. A new structure of a zero-voltage soft-switching high-frequency resonant inverter was proposed in [16]. The new power supply topologies, enabling high-performance induction heating by using the magnetic energy recovery, was proposed to add independent controllability of the frequency and current in [17]. A zero-voltage switching high-frequency resonant inverter with a load-power adaptive dual pulse modulated current phase controlled was presented for induction heating applications in [18]. Currently, most tundish heating power supply in China adopts the traditional topological structure, which is composed of multi-winding transformer, three-phase diode rectifier, and cascaded H-bridge converter. Specifically, AC/AC conversion from three-phase to single-phase can be easily realized. However, in the whole process of continuous casting, tundish exhibits thermal loss in varying degrees, especially during the abnormal casting periods such as the initial stage of casting, ladle exchange, and the end of casting, which inevitably leads to large temperature drop. Simultaneously, the steel water corresponds to nonlinear load, and its impedance varies with weight and temperature of the heated steel water. Most of electromagnetic induction heating power supplies are not treated well due to these factors [19], [20].

In this paper, an intelligent temperature control algorithm based on cloud controller is proposed, which can accurately
track the output current of power supply for tundish electromagnetic induction heating and realize constant temperature control of the tundish steel water. Reactive power compensation is performed in the induction heating coil and capacitor, and the power factor of the power supply system is improved.

II. TOPOLOGY OF POWER SUPPLY FOR TUNDISH ELECTROMAGNETIC INDUCTION HEATING SYSTEM

The tundish electromagnetic induction heating system is powered by a high-power cascaded variable frequency power supply to the induction coil. Thereby, an electromagnetic field is formed, which generates a large current in the ladle to realize the heating of the molten steel. The topology of the tundish electromagnetic heating high-power cascaded variable frequency power supply is shown in Fig. 1. There are six power units. The fore-stage three-phase rectifier and back-stage single-phase full-bridge inverter are adopted in each power unit, which is supplied through the secondary winding of the transformer. The secondary winding is in delta connection to reduce input harmonic current. The modularization degree and redundancy of the whole power system are improved by adopting the modularization design concept of power units. It is very convenient to take out each power unit module from the rack and replace the same, which enhances the safety and reliability of the system. Conversely, when the power supply fluctuates, it ensures the stability of the DC-side voltage and increases the transmission density of the power unit.

![Fig. 1. Topology of power supply for tundish electromagnetic induction heating system.](image)

In Fig. 1, $L_s$ is the connection inductance on the AC input side; $u_a$, $u_b$, and $i_{sc}$, where $x = a, b, c$, are the three-phase AC input voltage and current, respectively; $C_1$ and $C_2$ are the series capacitors on the rectifier side; and $C$ is the load-side reactive power compensation capacitor. Six power units are cascaded, and the carrier phase shift modulation strategy is adopted. We assume that the voltage of a sub-module corresponds to $u_x$, and the output voltage can be up to 27 levels from $-13u_x$ to $13u_x$.

III. CONTROL STRATEGY OF POWER SUPPLY FOR TUNDISH ELECTROMAGNETIC INDUCTION HEATING SYSTEM

The general control strategy of high-power-cascaded variable-frequency power supply for tundish electromagnetic induction heating system consists of the following three parts: the control for the fore-stage three-phase rectifier, the control for the back-stage full-bridge inverter, and the constant temperature control for the molten steel tundish. The corresponding control targets include the input current of the fore-stage rectifier, output load current of the back-stage inverter, and the temperature of the tundish, respectively.

A. Control of Fore-stage Rectifier

The power unit 1 in Fig. 1 can be used as a fore-stage rectifier circuit:

$$
\begin{bmatrix}
u_a \\ u_b \\ u_c\
\end{bmatrix} =
\begin{bmatrix}
u_{ma} \\ u_{mb} \\ u_{mc}\
\end{bmatrix} - L_s \frac{d}{dt} i_{sc}
$$

(1)

where $u_a, u_b, u_c$ are the phase voltages of the inverter.

$$
\begin{bmatrix}
u_a \\ u_b \\ u_c\
\end{bmatrix} = \begin{bmatrix}
 s_{Ra} \\ s_{Rb} \\ s_{Rc} 
\end{bmatrix}
$$

(2)

where $s_{Ra}$ equals 1 and −1 for upper and lower bridge arm conductions, respectively.

The rectifier switching signals are expressed as:

$$
\begin{bmatrix}
s_{Ra} \\ s_{Rb} \\ s_{Rc}\
\end{bmatrix} = \frac{L_s}{u_d T_s} \begin{bmatrix}
i_{sa}(k) \\ i_{sb}(k) \\ i_{sc}(k)\
\end{bmatrix} + \begin{bmatrix}
u_{ma}(k) \\ u_{mb}(k) \\ u_{mc}(k)\
\end{bmatrix}
$$

(3)

where $u_d$ is the DC-side voltage in the rectifier; $T_s$ is the switching period time of the insulated gate bipolar transistor; and $k$ is discrete time. As shown in the above equations, the given input current signal of the rectifier shall be determined to obtain the switching signals of the rectifier.

The power $P_s$ generated by the grid-side voltage of each power unit is equally distributed to each power unit and can be obtained as:

$$P_s = \frac{3u_l I_l}{2}
$$

(4)

where $U_l$ is the amplitude of the grid-side voltage of the power unit 1. The power $P_s^*$ denotes the active power of the given load. Additionally, $P_s = P_s^*/6$. Hence, the amplitude of the rectifier input current $I_l$ is as follows:

$$I_l = \frac{2P_s^*}{6 \times 3U_l} = \frac{P_s^*}{9U_l}
$$

(5)

The tracking error $\Delta u$ between the given DC-side voltage value $u_d^*$ and actual DC-side voltage value $u_d$ is obtained by the proportional integral (PI) regulator to obtain a DC-side current adjustment signal $I_{lc}$. The amplitude of the given input current of the rectifier is obtained as:

$$I_{lc} = I_{lc} + I_l = \frac{P_s^*}{9U_l} + k_p \Delta u + k_i \int \Delta u dt
$$

(6)

where $k_p$ and $k_i$ are the parameters of the PI. The currents of the AC-side of the fore-stage rectifier are then obtained by
multiplying the synchronous sinusoidal signals corresponding to the three-phase grid voltages as follows:

\[
\begin{bmatrix}
I_{a}^* \\
I_{b}^* \\
I_{c}^*
\end{bmatrix} = I^* = \begin{bmatrix}
\sin(\omega^* t) \\
\sin(\omega^* t - \frac{2}{3}\pi) \\
\sin(\omega^* t + \frac{2}{3}\pi)
\end{bmatrix}(7)
\]

where \(\omega^*\) is the reference angular frequency, which is obtained by phase locked loop (PLL) from the input voltage \(u_{sa}\). We substitute (7) into (3), and the phase switching signals of the fore-stage rectifier in power unit 1 are obtained.

The fore-stage three-phase rectifier of the power unit mainly controls the input current and realizes the accurate tracking of the input current while solving the problem of DC-side voltage fluctuation. We consider power unit 1 as an example, and the control block diagram of the fore-stage rectifier is shown in Fig. 2. The remaining power unit control methods are the same as that of the power unit 1.

Fig. 2. Control of fore-stage rectifier.

B. Control of Back-stage Inverter

The back-stage single-phase inverter can be used to control the output current and thermostatic over-heating of the molten steel in the tundish. However, the equivalent impedance of the loaded molten steel, i.e., the equivalent resistance \(R_e\) and inductance \(L_e\) change with the temperature. Thus, the low-frequency output current is affected, which further affects the temperature of the molten steel. Conversely, during the tundish pouring, the heat dissipation of the molten steel to the environment decreases the temperature of the tundish. Thus, the temperature of the molten steel is in an unstable state and deviates from the target temperature. Therefore, it is necessary to combine the cloud controller to obtain the relationship between the temperature of the molten steel and the change in output currents.

The control diagram of the back-stage inverter is shown in Fig. 3, where PWM stands for pulse width modulation. The pulse signals \((s_{a1}, s_{b1}, s_{a2}, s_{b2})\) are triggered by the power switch device in each inverter via carrier-phase shift modulation. The details are as follows.

1) Control for Output Current

As shown in Fig. 1, the induction heater is similar to a single-phase transformer. The multi-turn coil is equivalent to the primary side of the transformer, and the molten steel flowing in the channel is equivalent to the secondary side. When the primary side feeds the AC, the flux \(\Phi\) in the closed magnetic circuit is established. The induction voltage is induced by \(\Phi\) in the channel of molten steel as follows:

\[
E = \frac{d\Phi}{dt}
\]

With the conductivity of the molten steel, the induction current is induced in the molten steel for heating.

In the process of casting, the temperature of the molten steel injected into the tundish is not constant. Based on the properties of steel itself, the impedance of molten steel increases with temperature. The changing impedance of molten steel is expressed as a linear relation with the temperature as:

\[
\begin{align*}
R_e &= R_{\text{init}} (1 + \Delta T \alpha) \\
L_e &= L_{\text{init}} (1 + \Delta T \alpha)
\end{align*}
\]

where \(R_{\text{init}}\) and \(L_{\text{init}}\) are the initial resistance and inductance of molten steel, respectively; \(\Delta T\) is the changing temperature; and \(\alpha\) is the changing temperature factor.

In order to ensure that the temperature of the molten steel can rise rapidly and steadily, the power supply for tundish electromagnetic induction heating system should operate under full-power condition. The compensation capacitance \(C\) is used to compensate the inductive coil and steel water. Hence, the output voltage \(u\) and output current \(i\) exhibit the same phase, and the load is equivalent to a purely resistive load \(Z = R_e\). The effective value of the output current is calculated by:

\[
I_{\text{rms}} = \frac{P^*}{\sqrt{Z}}
\]

Simultaneously, in order to ensure that the molten steel load can operate in a constant temperature and superheated environment, the reference amplitude of the final output current is calculated by:

\[
I^* = \Delta I + I_{\text{rms}} = \Delta I + \frac{P^*}{\sqrt{Z}}
\]

where the regulated current \(\Delta I\) of the load temperature is obtained from the cloud controller. The reference output current value of the heating power supply is obtained as follows. \(\omega^*\) of the output current is given. The difference between the reference output current and actual output current is regulated by the proportional resonant (PR) regulator, and the obtained value is added to the actual output voltage to obtain the reference voltage value \(u^*\).
The reference output voltage \( u_i^* \) is divided by 6. This yields the following expression:

\[
u_i^* = u_i^* = u_i^* = u_i^* = u_i^* = \frac{u^*}{6} \quad (13)
\]

The reference output voltages of each power unit module \( u_1^*, u_2^*, u_3^*, u_4^*, u_5^*, u_6^* \) are obtained. Output voltage synchronization, power sharing, and redundant standby among the power unit are achieved in the control algorithm. The stability of the output voltage is improved.

2) Principle of Cloud Controller

Fuzzy theory can be applied to mathematically and precisely describe vague objects [21], [22]. Traditionally, a membership function of a fuzzy set is a one-to-one mapping from a space \( x \) to the unit interval \([0,1]\). Following the mapping, the uncertainty of an element belonging to the fuzzy concept becomes certain with a precise number. The uncertain characteristics of the original concept are not passed on to the next step of processing, which is not in accordance with the fuzzy thinking. However, with the model of membership clouds, soft computing can be implemented to exploit the tolerance and inheritance for the uncertainty and the imprecision or fuzziness and randomness [23].

The membership cloud is defined as follows. Let \( U \) be the set, \( U = \{x\} \), as the universe of discourse. \( C \) is a linguistic term associated with \( U \). The membership degree of \( x \) in \( U \) to the linguistic term \( C \), \( \mu(x) \in [0,1] \) is a random variable with a probability distribution. Subsequently, the distribution \( \mu(x) \) denotes the membership cloud.

A membership cloud is a mapping from the universe of discourse \( U \) to the unit interval \([0,1]\). Thus, the mapping from all \( x \in U \) to the interval \([0,1]\) is a one-point to multipoint transition and produces a membership cloud as opposed to a membership curve. The concept of membership cloud provides qualitative and quantitative characterization of linguistic atoms. The definition of membership cloud effectively integrates the fuzziness and randomness of a linguistic term in a unified manner. In the cloud, fuzziness lies at the center, and it may not relate to the probability. However, a probability is adhered to the fuzziness from a statistical viewpoint [23], [24]. The degree of membership from \( x \) to \( C \) is a probability distribution as opposed to a fixed value.

The computation process of a cloud controller includes three steps, i.e., clouded numerical value, cloud uncertainty reasoning, and numerical cloud.

First, the numerical values are clouded. \( R(E, \sigma) \) is assumed as a random function following a normal distribution, where \( E \) is the expected value and \( \sigma \) denotes the standard deviation. A normal random entropy with an expected value of \( E_\sigma \) and a standard deviation of \( H_\sigma \) is generated as:

\[
E'_\sigma = R(E_\sigma, H_\sigma) \quad (14)
\]

where \( E'_\sigma \) is the standard deviation; \( E_\sigma \) is a measure of qualitative concept ambiguity which reflects the range of values accepted in the universe; and \( H_\sigma \) is the entropy of \( E_\sigma \).

Then, a normal random number with the expected value of \( E_i \) and \( E'_i \) is generated as:

\[
x_i = R(E_i, E'_i) \quad (15)
\]

Finally, the membership function with the normal distribution form is obtained as:

\[
\mu_i = \exp \left( -\frac{(x_i - E_i)^2}{2(E'_i)^2} \right) \quad (16)
\]

where \( x_i \) is the cloud droplet that exhibits the degree of membership \( \mu_i \). A few cloud droplets form the cloud \( G(E_i, E_\sigma, H_\sigma) \). A diagram of a cloud is shown in Fig. 4.

Based on the definition and Fig. 4, the degree of membership \( \mu_i \) is not constant and always exhibits subtle changes. However, the changes do not affect the general characteristics of the cloud. The digital characteristics of the membership cloud are characterized by three values as follows: \( E_i \), \( E_\sigma \), and \( H_\sigma \). The increases in \( E_\sigma \) increase the range of values accepted by the concept and make the concept more blurred. Additionally, \( H_\sigma \) reflects the degree of dispersion of cloud droplets. The increases in the super entropy increase the dispersion of cloud droplets, the randomness of membership, and the “thickness” of the cloud [21]-[23]. It is proved that more than 99.74% of the cloud drops are scattered in the range \([E_i - 3E_\sigma, E_i + 3E_\sigma]\) [23], [25].

Second, the cloud uncertainty reasoning is done based on cloud generators. The cloud controller is composed of cloud generators, which includes the forward cloud generator and reverse cloud generator. If \( G_d(E, E_\sigma, H_\sigma) \) is a one-dimensional normal membership cloud model and satisfies (14)-(16), it is termed as the forward one-dimensional cloud generator \( CG_d \), as shown in Fig. 5(a), where \( e \) and \( e' \) are the deviation and the deviation difference of the input signal, respectively.

If \( G_d(E_\sigma, E_\sigma, H_\sigma) \) is a one-dimensional normal membership cloud model and satisfies the following expression:

\[
E_x = R(E_\sigma, H_\sigma) \quad (17)
\]

\[
z_i = E_x \pm \sqrt{-2 \ln(\mu(e, e'))} E'_\sigma \quad (18)
\]

Then three digital characteristic values include \( E_\sigma \), \( E_\sigma \), and \( H_\sigma \). It is termed as the reverse one-dimensional cloud generator \( CG_e \). When \( e < E_\sigma \), the ± in (18) is assumed as a negative deviation.
tive sign. When \( e > E_{ec} \), the \( \pm \) in (18) is assumed as a positive sign as shown in Fig. 5(b).

\[ E_{ec} \]

\[ E_{ec}, H_{ec} \]

\[ CG_A \]

\[ \mu(e, e_c) \]

\[ CG_B \]

\[ Z_i \]

![Fig. 5. Cloud generators and single-rule generator. (a) Forward cloud generator. (b) Reverse cloud generator. (c) Single rule generator.](image)

The cloud uncertainty reasoning is based on cloud generators as shown in Fig. 5(c). A single rule can be described as if \( A \) then \( B \). Additionally, \( A \) and \( B \) denote the qualitative language values.

Third, the resulting cloud is numerical. The numerical output can be obtained by the average value or the weighted average value of \( m \) cloud droplets \( z_i \).

3) Cloud Controller for Tundish Steel Water Temperature Control

The deviation between the actual detected tundish molten steel temperature and the given temperature \( e \) and deviation difference \( e_c \) are used as input signals of the cloud controller. Based on different \( e \) and \( e_c \), the cloud controller is used. \( \Delta f \) of the back-stage inverter is then obtained.

The cloud model of \( e \) is represented by a numerical feature as \( Ge(e_{rec}, e_{rec}, H_{rec}) \). The cloud model of the deviation \( e_c \) is represented by a numerical feature as \( Ge(e_{rec}, e_{rec}, H_{rec}) \). In the paper, the golden section method [21] is used to generate seven clouds for the input signal, and this is used to denote the language value. Parameters of the forward one-dimensional cloud controller are shown in Table I.

**TABLE I**

| Order | Get\( E_{rec}, E_{rec}, H_{rec} \) | Get\( E_{rec}, E_{rec}, H_{rec} \) | Get\( E_{rec}, E_{rec}, H_{rec} \) |
|-------|---------------------------------|---------------------------------|---------------------------------|
| 1     | Ge\((-10, 3.3, 0.4) \)          | Ge\((-3, 0.9, 0.3) \)          | Ge\((-3, 0.1, 0.3) \)          |
| 2     | Ge\((-3.8, 2.1, 0.3) \)         | Ge\((-1.2, 0.6, 0.2) \)        | Ge\((-1.2, 0.6, 0.2) \)        |
| 3     | Ge\(-1.9, 1.3, 0.2 \)           | Ge\(-0.6, 0.2, 0.1 \)          | Ge\(-0.6, 0.2, 0.1 \)          |
| 4     | Ge\(0, 0.8, 0.1 \)             | Ge\(0, 0.4, 0.05 \)            | Ge\(0, 0.4, 0.05 \)            |
| 5     | Ge\(1.9, 1.3, 0.2 \)            | Ge\(0.6, 0.2, 0.1 \)           | Ge\(0.6, 0.2, 0.1 \)           |
| 6     | Ge\(-3.8, 2.1, 0.3 \)           | Ge\(1.2, 0.6, 0.2 \)           | Ge\(1.2, 0.6, 0.2 \)           |
| 7     | Ge\(10, 3.3, 0.4 \)             | Ge\(3, 0.9, 0.3 \)             | Ge\(3, 0.1, 0.3 \)             |

We consider the input signal deviation as an example. The seven cloud curves of \( e \) are shown in Fig. 6, and the number of cloud droplets per cloud is 1000.

The cloud controller implements a mapping relationship between the deviation input and controller output. A forward two-dimensional cloud generator and reverse one-dimensional cloud generator are used to construct qualitative rules with “and” conditions as shown in Fig. 7. The definitions of the forward two-dimensional cloud generator and reverse one-di-

![Fig. 6. Clouds of \( e \).](image)

The forward cloud generator is constructed using the three digital feature values of the cloud. If \( G_A(E_{rec}, E_{rec}, (H_{rec}, H_{rec})) \) is a two-dimensional normal membership cloud model and satisfies the following expression:

\[ E_{rec} = R(E_{rec}, H_{rec}) \]  
\[ E_{rec} = R(E_{rec}, H_{rec}) \]

\[ \mu(e, e_c) = \exp \left\{ -\frac{(e - E_{rec})^2}{2E_{rec}^2} + \frac{-(e - E_{rec})^2}{2E_{rec}^2} \right\} \]

Then, it is termed as the forward two-dimensional cloud generator \( CG_A \).

The cloud controller proposed in the study consists of two-condition multi-rule uncertainty reasoning and the weighted average processing.

In Fig. 7, the input signals correspond to \( e \) and \( e_c \), and the output corresponds to \( \Delta f \). Additionally, \( CG_A \) corresponds to a forward two-dimensional cloud generator, and \( CG_B \) corresponds to a reverse one-dimensional cloud generator.

![Fig. 7. Diagram of cloud controller with cloud generators.](image)

As shown in Fig. 7, the reasoning part is realized by the forward cloud generator and reverse cloud generator. The cloud controller exhibits \( N(N = 49) \) conditional rules, which is formalized as follows.

If \( X = e, Y = e_c \), then \( Z = \Delta f(\mu_{49}) \). The input \( e \) and \( e_c \), stimu-
late different forward two-dimensional cloud generators $CG_1$ to generate different $\mu_{d0}$. And $\mu_{d0}$ then passes through $CG_1$ to generate a large number of cloud droplets $\Delta I_i(\mu_{d0})$ which are weighted and finally obtained. The output $\Delta I$ corresponds to the inputs $e$ and $e_r$. We consider the weighted average of $m$ cloud droplets as the output, which is expressed as:

$$\Delta I = \frac{\sum_{i=1}^{m} \Delta I_i(\mu_{d0})}{\sum_{i=1}^{m} \mu_{d0}}$$  \hspace{1cm} (22)$$

We substitute $\Delta I$ into (12), and the reference output current value of the heating power supply is finally obtained.

IV. SIMULATION AND EXPERIMENT

A. Simulation and Analysis

The simulation model of power supply for tundish electromagnetic induction heating system in shown in Fig. 1 is established to verify the validity and accuracy of the control method proposed for power supply for tundish electromagnetic induction heating system. The AC-side voltage is 400 V and the frequency is 50 Hz. The number of cascaded modules is 6. The load current frequency is 200 Hz. The simulation results are shown in Fig. 8.

The input current waveform of the rectifier in the power unit 1 is shown in Fig. 8(a). The other power unit modules exhibit the same input current waveform. Figure 8(b) shows the DC-side voltage waveforms of the six power units. The DC-side voltage of each power unit remains stable with a deviation of approximately 5 V. Figure 8(c) shows the output power and its reference value, and the output power can stably track the reference value.

The power factor of the tundish is low. Thus, capacitor $C$ is used to compensate the reactive power. The output voltage $u$ and current $i$ exhibit the same phase as shown in Fig. 8(d). The load is equivalent to a purely resistive load, which increases the power factor of the system.

B. Experiment and Analysis

The power supply for tundish electromagnetic induction heating system is developed and applied to a tundish induction heating device. Experiments are performed to verify the validity and accuracy of the proposed control method. The experimental results are shown in Fig. 9.

In Fig. 9(a), the input current of the rectifier in the power unit 1 exhibits a good waveform, and the input currents of other power units exhibit the same waveforms. Figure 9(b) shows the DC-side voltage waveforms of the six power units. The DC-side voltage of each power unit remains stable. Figure 9(c) shows the output power and its given reference value, and the output power can stably track the reference value. In Fig. 9(c), $P_{ref}$ is the rated load power and $P_o$ is the load power. The output voltage $u_o$ and current $i_o$ exhibit the same phase as shown in Fig. 9(d), and the power factor is high.

V. CONCLUSION

We propose an intelligent control algorithm based on cloud control, which is applied to a tundish electromagnetic induction heating system. The topology structure of high-power-cascaded power supply for tundish electromagnetic induction heating system is given. The power supply consists of six power units, and each of them consists of a three-phase rectifier and a single-phase inverter. A stable DC voltage can be obtained from the three-phase rectifier that is supplied to the inverter. An intelligent control algorithm based on a cloud controller is proposed to control the temperature. The cascaded power supply can use the redundant standby module in a timely manner to stabilize the output when the module is faulty. Voltage synchronization, power sharing, and redundancy standby are achieved among the power modules. The simulation and experiment are performed separately. The results verify the accuracy and effectiveness of the proposed method.
Fig. 9. Experimental result. (a) Three-phase PWM input current. (b) DC-side voltage. (c) Load power and given power. (d) Load voltage and load current.

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Xinxing Xiang received the B.E. degree from the School of Electronic Information, Wuhan University, Wuhan, China, in 2005. He is currently working towards the Ph.D. degree in the College of Electrical and Information Engineering, Hunan University, Changsha, China. His research interests include electromagnetic induction heating technology, static var compensator and modular multilevel converter.

An Luo received the B.S. and M.S. degrees in industrial automation from Hunan University, Changsha, China, in 1982 and 1986, respectively, and the Ph.D. degree in fluid power transmission and control from Zhejiang University, Hangzhou, China, in 1993. Since 2003, he has been a Professor at Hunan University, Changsha, China, where he also serves as the Chief of National Electric Power Conversion and Control Engineering Technology Research Center. He was elected to the Chinese Academy of Engineering in 2015. His research interests include power conversion, harmonics suppression and reactive power compensation, and electric power saving.

Yan Li received her B.S., M.S., and Ph.D. degrees in automation, disaster prevention, and mitigation engineering and pattern recognition and intelligent system from Central South University, Changsha, China, in 1999, 2003, and 2007, respectively. She also performed research works in the electrical engineering post-doctoral research station of Hunan University, Changsha, China. Her current research interests include intelligent control, power quality, power control, and fault diagnosis of electrical machines.