Analysis on impacts of domestic air source heat pumps to distribution networks in coal-to-electricity projects

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Abstract. As an air source heat pump unit can be used for building heating at a high operating efficiency, it is used more and more widely in the coal-to-electricity project. However, due to the voltage sag, the current surge and the harmonics caused by its using, the power quality problems should be considered with the large-scale units of the air source heat pump being connected to rural distribution networks. The working principles and the types of the domestic unit are introduced. The power quality problems are discussed with the parameters and the actual measurement data of the units in the distribution networks. The starting and operational characteristics of different air source heat pumps are compared. The voltage sags in a rural distribution network are simulated and analyzed during the starting process of the air source heat pump units. The corresponding solution measures are given for the problems caused by the large-scale units of the domestic air source heat pump.

1. Introduction

A heat pump unit is a device that transfers heat energy from a source of heat, such as outside air and underground water, to a destination, i.e. a heat sink [1]. It uses a small amount of electric power to transfer energy from the heat source to the heat sink. The unit can be used for both building heating and cooling at a high operating efficiency as an environmentally-friendly and reliable means of maintaining thermal comfortable in an indoor space. And more and more heat pump units are used for indoor environmental control as a means of reducing net energy consumption and hence emissions of greenhouse gases [2].

Coal-to-electricity projects have been applied in northern China in recent years, which directly consume electricity instead of coal in the energy consumption to heat home in the winter [3]. The projects can increase the proportion of electricity in terminal energy consumption, and fundamentally solve the problems that restrict sustainable development of human society such as energy environment and climate change, especially the haze problem in northern China. There are more heat pump units applied in domestic electric heating radiators now because to their high operating efficiency. Practical studies have shown the potential of the heat pump units to drastically reduce greenhouse gases, in particular CO\textsubscript{2} emissions [4]. Among the heat pump units, however, air source heat pump (ASHP) units are relatively easy and inexpensive to install, and have therefore been the most widely used type of the heat pump units [5]. When properly installed, an air source heat pump unit can deliver one-and-a-half to three times more heat energy to a home compared to the consumed electric energy because the ASHP unit moves heat. When the ASHP units operate in heating mode at low temperatures in high
humidity environments, frost forms and accumulates on the surface of its outdoor coils, which adversely degrades the operating efficiency of ASHP units rapidly. Extensive experimental investigations have been carried out on ASHP units to study their operating performance under frosting and defrosting conditions [6, 7].

The performance problems of the ASHP units were considered from the perspective of ASHP, and the influence of the units on the operation status of distribution networks was not involved in the above literatures. Based on the basic characteristics of the ASHP units, the power quality problems such as the air voltage sag and the harmonics caused by the units are discussed with the parameters of the units and the actual measurement data in the distribution networks. According to the information and data of the low voltage (LV) distribution network in an actual coal-to-electricity project, the problems are simulated and analyzed with the large-scale the ASHP units being connected to the LV distribution network by using the SINCAL simulation platform.

2. Basic Performance of ASHP

2.1. Working Cycle of ASHP
The ASHP units absorb heat from the outside air, which is different from a ground source heat pump unit. The heat can then be used to heat radiators, underfloor heating systems, or warm air convectors and hot water in home. The units can get heat from the air even when the temperature is 15 °C.

The components of an ASHP unit include the ducts, compressors and working fluid. Heat from the air is absorbed at low temperature by the ASHP refrigerant in a cycle that pulls heat from the outside air as it vaporizes and releases heat when it is condensed. The working fluid then passes through a compressor where its temperature is increased, and transfers its higher temperature heat to the hot water-filled radiators, the underfloor heating or domestic hot water supply of a house. The vaporization and the condensation of the refrigerant are facilitated by applying an electric pump that forces the air through an evaporator and then into a condenser. Electric power is required by the unit to drive the pump. The fluid releases heat as it is forced to condense into a high pressure liquid. In turn, heat is absorbed by the unit while the liquid evaporates.

2.2. Types of ASHP Units
There are two main types of ASHP units according to different heat exchange media indoors.

1) Air-to-water. An air-to-water unit of ASHP distributes heat via a wet central heating system. The ASHP unit works much more efficiently at a lower temperature than a standard boiler system would, which makes them more suitable for underfloor heating or larger radiators.

2) Air-to-air. An air-to-air unit of ASHP produces warm air which is circulated by fans to heat house. It is unlikely to provide home with hot water as well.

There are four basic types of ASHP units according to different installation position of ASHP components.

1) Split Systems. Split ASHP units are the most common ASHP type in the coal-to-electricity projects. The split unit has one heat exchanger coil indoors and one heat exchanger coil outdoors. The compressor compresses the refrigerant and then forces it indoors where it releases heat into the supply ducts. Once in the duct, heat is moved through the house by a fan. The working fluid then moves through the expansion valve outdoors where it evaporates into a gas, absorbing heat, before being returned indoors. Cool air indoors is circulated back to the fan via return ducts. The indoor coils transfer heat from the refrigerant as it condenses back into a liquid.

2) Packaged Systems. Some ASHP units are packaged systems. Both the coils and the fan of the packaged systems are installed outdoors.

3) Ductless Room Heat Pumps. Ductless room heat pumps are essentially another form of the packaged system that does not use ductwork. These pumps can efficiently heat a room or small house with an open floor plan. They can be installed in a window or through a hole in the wall.

4) Hybrid Systems. A fourth type of ASHP units is a hybrid system. The system is essentially one of the above ASHP types that are permanently coupled with variable electric heating.
There are two types of ASHP units according to different control form of the compressor speed in the ASHP unit.

1) Fixed-speed ASHP. Because the power supply frequency cannot be changed, the compressor speed of the fixed-speed ASHP unit is constant. Normally the ASHP unit operates intermittently in the on or off mode to adjust the heating capacity to the load required in the house with a fixed-speed. If the temperature reaches the set value, the compressor stops working. Otherwise, it starts working and adjusts the temperature by constantly opening and stopping the compressor. When the unit operates in this way to provide the heat needed during the entire cycle, it has to supply heat at higher temperature during the cycle. The technical specifications provided by the manufacturer of a 6 HP ASHP unit with the fixed-speed in the coal-to-electricity projects are shown in Table 1. The coefficient of performance (COP) of an ASHP unit is used for heating and defined as follows:

\[
COP = \frac{q_{ASHP}}{P_{ASHP}}
\]

where \( q_{ASHP} \) is the thermal power provided by the ASHP unit in kW, \( P_{ASHP} \) is the electric power input to the ASHP unit in kW. During cooling mode the definition remain the same and follow to calculate the energy efficiency ratio (EER) by replacing the condenser heat flow rate with the evaporator cooling power.

2) Variable-speed ASHP. If a variable-speed compressor is used, the ASHP unit could simply follow the load, taking advantage at partial loads from the oversized heat exchangers and thus increasing its efficiency. For example, when it is the coldest time, there is little heat in the air, and the heat efficiency of the ASHP unit decreases. At this time, the speed of the heat pump compressor can be improved by a frequency converter. In this way, the heat performance of the ASHP unit is improved to a certain extent to get rapid yielding water. When the outdoor air temperature rises, the working speed of the heat pump compressor can be reduced. At the same time to meet the needs of mild heating, the power consumption of the unit is reduced and the heating process is more economical. The technical specifications provided by the manufacturer of a 7 HP ASHP unit with the variable-speed in the coal-to-electricity projects are shown in Table 2.

3. Effect of ASHP Units on Power Quality

3.1. Evaluation of Power Quality

According to the relevant standards of the power quality issued in China [8, 9], the main indexes of evaluating the power quality in the distribution network are the voltage and the harmonics. Based on the actual investigation and theoretical analysis of the ASHP unit operation, it is determined that the influence of the ASHP units on the power quality of the LV distribution network is mainly in two aspects, the voltage sag and the harmonics.

| Operation State               | Cold | Thermal at -7.6 °C | Thermal at -12.0 °C |
|------------------------------|------|---------------------|---------------------|
| Rated capacity /kW           | 12.0 | 13.5                | 11.4                |
| Rated input power /kW        | 4.85 | 5.20                | 4.90                |
| EER or COP /p.u.             | 2.47 | 2.59                | 2.32                |
| Rated input current /A       | 29.0 | 30.0                | 29.3                |
| Maximum input current /A     | 39.0 |                     |                     |
| Maximum input power /kW      | 6.76 |                     |                     |
| Rated voltage /V~             | 220  |                     |                     |
| Maximum discharge pressure /MPa | 2.8 |                     |                     |
| Maximum inspiratory pressure /MPa | 0.8 |                     |                     |
| Refrigerant gas              | R22 / 5.0kg |                 |                     |
| Ambient temperature /°C       | -25–45 |                 |                     |
### Table 2. Technical specifications of a 7 HP ASHP unit with variable-speed

| Operation State | Cold  | Thermal at -7.6 °C | Thermal at -12.0 °C |
|-----------------|-------|--------------------|---------------------|
| Rated capacity /kW | 14.0  | 16.5               | 13.5                |
| Rated input power /kW | 5.07  | 6.77               | 6.00                |
| EER or COP /p.u.   | 2.76  | 2.435              | 2.25                |
| Rated input current /A | 23.1  | 30.8               | 27.3                |
| Maximum input current /A | 45.0  |                     |                     |
| Maximum input power /kW |       |                     |                     |
| Rated voltage /V~   | 220   |                     |                     |
| Ambient temperature /°C | -25~45|                     |                     |

The fixed-speed ASHP unit needs a lot of current during startup. The startup current is usually 4~7 times of the maximum operation current, which is easy to cause obvious voltage sag in the LV distribution network. Although variable-speed conversion technology can properly reduce the starting current of a single heat pump, the harmonic content caused by the variable-speed ASHP unit can not be neglected. The variable-speed compressor of the ASHP unit may inject the harmonic current, and the total harmonic distortion rate of the distribution system is possibly larger than the permissible value of the distribution network, which is set in the corresponding national standard in order to limit the high order harmonic content in the distribution network.

#### 3.2. Measurement of Voltage Sags and Harmonics

Several villages are selected for the measurement of voltage sags and harmonic currents caused by the different types of ASHP units, which have completed the coal-to-electricity projects in the suburbs of Beijing. FLUKE 434 is selected as the measuring instrument. The measurement time is 10 min, and the measured harmonic result is the average of the harmonic current. Ambient temperature is about 0~16 °C. The operation voltages of the measurement nodes are near 220V when the ASHP units are switched off.

The variables of two brands of the ASHP units, such as starting current, residual voltage, the duration of transient process of voltage sags, and harmonic currents, are measured respectively. The 6 HP ASHP units uses the entropy increase technology of the compressor and the jet, which does not change the run speed of the compressor, i.e. fixed-speed, and improves the working efficiency of the compressor through simple loading and unloading mechanical movement. Its basic specifications are shown in Table 1. The other measurement data are shown in Table 3 without the harmonic content generated by the unit because it is quite small.

### Table 3. The starting characteristic data of the 6 HP ASHP unit.

| Maximum startup current /A | Maximum active power /kW | startup voltage /V | Duration of transient process /s |
|---------------------------|--------------------------|-------------------|----------------------------------|
| 146.16                    | 15.97                    | 191.89            | 0.21                             |

The maximum startup current of the fixed-speed ASHP unit is 146.16 A, which was about 4.87 times of the rated heat current due to the non-speed starting control during the starting process. Its minimum operating startup voltage is 191.89 V, which is lower than the threshold of the voltage sags of the LV distribution network, i.e. 220 × (1 – 10%) =198 V. Therefore, after the fixed-speed ASHP unit is connected to the distribution network, a large voltage drop will be generated in the LV distribution network during the start-up process, which may affect the normal operation of the distribution network.

The 7 HP ASHP units use the frequency conversion technology. Its technical specifications are shown in Table 2. The soft start of the compressor speed conversion is applied and the current change is not obvious in the starting process. The starting voltage is basically stable at about 220V. During the
operation of the ASHP unit, its THD (total harmonic distortion) of the operation current is about 11.5~23.6%, as shown in Figure 1.

![Figure 1. Current spectrum diagram of the 7HP ASHP unit](image)

Therefore, some attention should be paid to the design for the variable-speed compressor of the ASHP unit, and the influence of the high order harmonics should be considered on the power supply. The harmonic current should be limited to meet the requirements of the corresponding standard when the large-scale variable-speed ASHP units are connected to LV Distribution Networks.

4. Simulation Analysis of Application of Large-scale ASHP Units
In order to analyze the influence of the voltage sags generated by the ASHP units connected to the LV distribution network, the operation state of the LV distribution network, shown in Figure 2, of a village is simulated. The coal-to-electricity project has been carried out in the village.

![Figure 2. LV distribution network diagram of a village.](image)

The LV distribution network is connected to the distribution transformer in 315 kVA, the type being S11-315/10 and the voltage ratio being 10kV / 0.4kV. All users are basically evenly distributed in each phase. There are six branch lines, from B1 to B6, in addition to the main line where the node number is from 1 to 16 and the line type is JKLYJ-120. The type of all the branch lines is JKLYJ-70. The resistance and reactance of the one km length of JKLYJ-120 are 0.27 Ω/km and 0.297 Ω/km, respectively, and JKLYJ-70, 0.46 Ω/km and 0.315 Ω/km. The line length between two nodes is assumed to be 400 m for the purpose of simplicity. The power load of node 5, 16, B1- 1, B1-3, B1-4, B2-1, B2-6, B3-2, B4-2, B5-2, B5-3 and B6-2 is assumed to be 3 kW, and the power load of node 10, B1-5, B2-4, B2-5, B3-1, B4-3, B5-1 and B6-3 is 4.5 kW. The simulation model of the LV distribution network is constructed in SINCAL, a simulation platform developed by Siemens.

When different simulation scenes are established, the permeability ratio of the ASHP units, represented as \( r_{Per} \) in per unit (p.u.), may be considered

\[
r_{Per} = \frac{P_{ASHP}}{P_{All}} = \frac{P_{ASHP}}{(P_{ASHP} + P_{LV})}
\]

where \( P_{ASHP} \) is the total power of the steady operation of all the ASHP units in kW, \( P_{All} \) is the total power of the LV distribution network in kW, \( P_{LV} \) is the total power of the other ordinary load of the LV distribution network in kW.
It is assumed that all the ASHP units connected to the network are the same as those of the 6 HP ASHP units with fixed-speed, their technical specifications and the startup measurement results are shown in Table 1 and Table 3, respectively. While \( r_{\text{Per}} = 0 \) with the load of all users in the LV distribution network, the voltage of node 16 is 0.973 p.u. If the ASHP units are only connected to the node 16 with \( r_{\text{Per}} = 0.173 \), the start of the ASHP units can cause a decrease of the terminal voltage of the LV distribution network, and the duration of the starting process is about 0.22 s. The minimum residual voltage of node 16 is about 0.834 p.u., i.e. 184.6 V, and the voltage is much lower than the threshold value of the voltage sags, 0.9 p.u., i.e. 198 V. The sudden voltage drop will affect the operation of other electrical equipment.

When the ASHP units are only connected to the node 8 and node 16 with the same capacity, although the voltage of node 16 is 0.922 p.u., i.e. 202.8 V, with \( r_{\text{Per}} = 0.347 \) in the normal operation state, the minimum residual voltage of node 16 is about 0.777 p.u., i.e. 170.9 V, while the heat pumps are starting, which is far below the voltage threshold, 0.9 p.u. Similar, when the ASHP units are only connected to the node 4, node 8 and node 16 with the same capacity, the voltage of node 16 is 0.913 p.u., i.e. 200.9 V, with \( r_{\text{Per}} = 0.52 \) in the normal operation state.

Therefore, the start of the ASHP units should be avoided at the same time as possible. It is necessary to guide the users to start ASHP units as orderly as possible to avoid multiple units to start at the same time. Some attention should be paid to the design, and the protection curve of the circuit breaker is reasonably selected to avoid the startup current of the fixed-speed ASHP units over the tripping current of the circuit breaker. The section area of the line should be large enough with large-scale ASHP units.

5. Conclusion
When the ASHP units are installed in the rural area with the coal-to-electricity projects, it is necessary to consider whether the new load demand of the ASHP units will be met according to the distribution transformer capacity and line parameters, there will be more harmonics and the node voltage will be too low. With the increase of permeability of the variable-speed ASHP units, the harmonic content of voltage and current will increase. It is necessary to take measures to suppress the harmonic content based on the actual situation of the LV distribution network. Through the start simulation of the fixed-speed ASHP units, the larger voltage sag may be caused during the heat pump starting process in the LV distribution network. The length and the section area of the distribution line affect the allowable permeability ratio of the ASHP units and the starting number of the units at the same time. In addition, it is necessary to guide the user to start ASHP units as orderly as possible to avoid multiple heat pumps to start at the same time.

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