Study on Power Quality Impacts of Rural Distribution Network with Large-scale Heat Pumps

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Abstract. With the advance of the "*Coal-to-electricity*" program in northern China, heat pump unitsare used more and more widely for rural household heating at a high operating efficiency. When large-scale heat pump units are connected to rural distribution networks, the power quality problems should be considered because of the voltage sag, the current surge, and the harmonics caused by the units. The typical feature, the efficiency index, the operation process and the types of the domestic heat pump units are introduced. The starting characteristics of different heat pump units are compared. Impacts on distribution networkswith heat pumpsare discussed,including the additional load forecast method of heat pump units and the power quality problems. The startup current of the fixed-speed heat pump is too large to cause voltage sag. The variable-speed heat pump may inject the harmonic current into distribution system.A rural distribution network are simulatedwith the actual measurement datain order to analyse the voltage sagsduring the starting process of the heat pump units with different permeability of the units. The corresponding simulation results can be used as the reference for the further implementation of the "*Coal-to-electricity*" program.

1. Introduction

Heat pumps are designed to obtain low-grade thermal energy from the natural air, water or soil, to do work through electric power, and to provide people with high grade thermal energy. A heat pump unit uses a small amount of electric power to transfer energy from the source of low-grade thermal energy to the heat sink. Heat pump technology was available in its current form in the 1930s, experienced a real boom after the first oil crisis in the 1970s, tested in cold climates in the 1980s. The market for heat pumps did not revive until the mid - 1990s and is currently experiencing high annual growth rates [1].

The application of the heat pumps can drastically reduce greenhouse gases, in particular CO_2 emissions [2]. In recent years "*Coal-to-electricity*" programs have been applied in northern China [3], which directly consume electricity instead of coal in the energy consumption to heat home in the winter, and fundamentally solve the problems that restrict sustainable development of human society such as energy environment and climate change, especially the haze problem. Because the heat pump units offer energy efficient and environmentally-friendly heating in domestic applications, they are applied more and more in domestic electric heating radiators in the programs. The heat pumps include the air source heat pump (ASHP) and the ground source heat pump (GSHP). An ASHP unit absorbs heat from the outside air, which is different from a GSHP unit that absorbs heat from groundwater or ground with a ground heat exchanger/collector.

The climate impacts of two heat pump units, ASHP and innovative GSHP, were compared for domestic heating, i.e. the energy consumption for space heating of a residential building [4]. To save energy consumed for spacing heating and enhance the indoor thermal environment, the performance improvement of the heat pumps has become one of the research foci in the relevant field, and some studies have been carried out on investigating the frosting, defrosting and low ambient heating performances of ASHP [5], [6]. The impacts of frosting evenness of outdoor coil were experimentally investigated on the heating performances of an ASHP unit [5]. A review of the advances in ASHP units was presented for the units to apply in cold climate, in which the related advanced units were divided into single-stage, dual-stage and multi-stage compression units [6]. A model of a GSHP unit with variable speed compressor, variable speed water pumps and variable speed fans is presented in order to evaluate the operation conditions of the maximum seasonal *COP* of the unit [7]. The development of a performance based model of a water-to-air variable capacity GSHP was presented, and the recommended control strategy is applied to vary the speed of the compressor for each mode of operation and to be able to switch from one mode to the other [8]. The performance problems of the heat pump units were considered in the above literatures, however the power quality impacts of the heat pump units on distribution networks were not involved.

The typical features of the heat pump units are introduced, and 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 of the rural distribution networks in this paper. According to the information and data of the distribution network in an actual "*Coal-to-electricity*" program, the power quality problems are simulated with the large-scale the heat pump units whichare connected to the rural distribution network.

2. Typical feature of heat pumps

2.1. Efficiency index of heat pump units

Measure of the relative efficiency of a heat pump unit can be expressed as the ratio of output to the energy consumed (both in kilowatts). The most commonly efficiency indexes of the heat pump units are coefficient of performance (*COP*) used for heating and energy efficiency ratio (*EER*) used for refrigeration.

COP of a heat pump unit is defined as follows:

$$COP = q_{\mathrm{HP}} / P_{\mathrm{HP}} \tag{1}$$

Where q_{HP} is the thermal power provided by the heat pump unit in kW, P_{HP} is the electric power input to the heat pump unit in kW. The power input P_{HP} and the refrigerating capacity q_{Source} of the low-temperature heat source together produce the heat flow q_{HP}:

$$q_{\mathrm{HP}} = q_{\mathrm{Source}} + P_{\mathrm{HP}} \tag{2}$$

If, for example, a heat pump with electrically driven power P_{HP} = 2 kW produces heat flow of q_{HP} = 6 kW, *COP* = 3. The difference of q_{Source} = 4 kW derives from the low-temperature heat source.

COP only applies to transient values. The annual average is applied, too. This is called an annual coefficient of performance (*ACOP*). A high *ACOP* is essential for the ecological and economical operation of a heat pump. For example, a heat pump can cover a heating requirement of 10500 kWh per year using 3000 kWh of electric energy with an *ACOP* = 3.5. *ACOP* of very good units can reach about 4. The practical values of *ACOP* for different types of heat pumps are shown as Table 1, which are gotten from a field test [1].

Table 1. Typical *ACOP* for heat pumps

Heat pump	Heat source	*ACOP* with underfloor heating	*ACOP* with radiators
GSHP (Brine/water)	Ground	3.6	3.2
GSHP (Water/water)	Groundwater	3.4	3.0
ASHP (Air/water)	Air	3.0	2.3

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During cooling mode the definition remain the same and follow to calculate *EER* by replacing the condenser heat flow rate with the evaporator cooling power.

2.2. Schematic systems of heat pumps

A heat pump is basically a machine in which an electrically driven pump generates heat from a low-temperature heat source. This heat is then used to provide heating or to produce hot water. Before a heat pump can even function, a low-temperature heat source must be available. The higher the temperature level of the heat source, the more efficiently the heat pump can work.

The heat from the heat source is absorbed at low temperature by a heat pump refrigerant in a cycle as it vaporizes and releases heat when it is condensed, as shown in Figure 1. 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 with the domestic heating pipelines. The vaporization and the condensation of the refrigerant are facilitated by applying an electric pump that forces the water or air through an evaporator and then into a condenser. In order to drive the pump,electric power is required.

2.3. Types of GSHP units

According to different heat sources which are available to houses, there are three main types of GSHP units, *ground water (water/water)*, *ground heat exchanger/collector (brine/water)* and *earth probing device (brine/water)*, as shown as Figure 2.

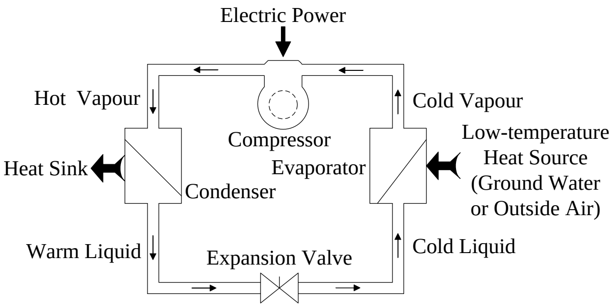

Figure 1. The schematic system of a heat pump

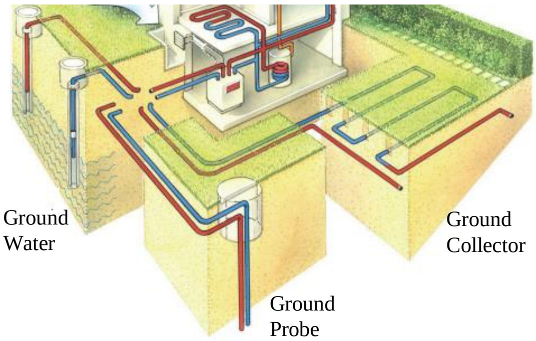

Figure 2. Heat sources for GSHP

According to different control form of the compressor speed in the GSHP unit, there are two types of GSHP units, *fixed-speed* and *variable -speed*.

Table 2. Specifications of a GSHP unit, Brand A

Operation State	Cold	Thermal at -7.6 ℃	Thermal at -12.0 ℃
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 working pressure of water system /MPa	0.3		
Maximum discharge pressure /MPa	2.8		
Maximum inspiratory pressure /MPa	0.8		
Pump capacity /(m^3/h)	1.72		
Refrigerant gas	R22 / 5.0 kg		
Ambient temperature / ℃	-25~45		

Because the power supply frequency cannot be changed, the compressor speed of the fixed-speed GSHP unit is constant. Normally the GSHP 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. A GSHP unit at a village in northern China is shown as Figure 3. The technical specifications provided by the manufacturer of a GSHP unit, Brand A, with the fixed-speed are shown in Table 2.

If a variable-speed compressor is used, the GSHP unit could simply follow the load, taking advantage at partial loads from the oversized heat exchangers and thus increasing its efficiency.

2.4. Types of ASHP units

ASHP has been widely applied to many parts of the world due to its simple structure and low initial cost. The ASHP units function at ambient temperatures as low as -20 ℃.

According to different heat exchange media indoors, there are two main types of ASHP units, *air-to-water* and *air-to-air*.

Figure 3. Outdoor part of a GSHP unit at a village in northern China

Figure 4. Outdoor part of an ASHP unit at a village in northern China

Table 3. Specifications of an ASHP unit,Brand B

Operation State	Cold	Thermal at -7.6 ℃	Thermal at -12.0 ℃
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 working pressure of water system /MPa		0.3	
Maximum discharge pressure /MPa		2.8	
Maximum inspiratory pressure /MPa		0.8	
Pump capacity /(m^3/h)		1.72	
Refrigerant gas		R22 / 5.0 kg	
Ambient temperature / ℃		-25~45	

According to different installation position of ASHP components, there are three basic types of ASHP units, *split systems*, *packaged systems* and *ductless room heat pumps.*

Split ASHP units are the most common type of ASHP in the "*Coal-to-electricity*" programs. These units have one heat exchanger coil outdoors and one heat exchanger coil indoors. The compressor, located outdoors as shown as Figure 4, 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.

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Some ASHP units are packaged systems. Both the coils and the fan of the packaged systems are installed outdoors. Then heated air is delivered to the interior from a duct system.
Ductless room heat pumps are essentially another form of 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.
Similarly, there are two types of ASHP units, *fixed-speed* and *variable-speed*, according to different control form of the compressor speed in the ASHP unit. The specifications provided by the manufacturer of a 6 HP ASHP unit, Brand B, with the fixed-speed in the "*Coal-to-electricity*" programs are shown in Table 3.

3. Impacts on distribution networkswith heat pumps

3.1. Additional load forecast of heat pump units

The additional load forecast formula is determined to the heat pump units for the "*Coal-to-electricity*" programs with difference load rate, simultaneity rate, and day conversion rate in different counties.

$$\Delta P = N \bullet P_{AV} \bullet \eta \bullet K_S \bullet k_d \tag{3}$$

where ΔP is additional load in kW, N is the number of additional households using the heat pump Units, P_{AV} is the additional average power per household in kW/ per household (It is approximately equal to 9kW, the expected load per household, minus the original average load per household), η is load rate in per unit, K_S is the load simultaneity rate of all households in per unit, k_d is the day conversion rate in per unit (according to the actual load situation in different counties, $k_d \approx 0.4 \sim 0.6$ in the summer, and $k_d \approx 1$ in the winter).

3.2. Power quality problems of heat pump units

The influence of the heat pump units on the power quality of the distribution network is mainly in two aspects, the voltage sag and the harmonic. The fixed-speed heat pump unit needs a lot of current during startup, and the startup current is usually 4~7 times of the maximum operation current, which is easy to cause obvious voltage sags in the distribution network. Although variable-speed conversion technology can properly reduce the starting current of a single heat pump, the variable-speed compressor 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.
The voltage sags and harmonic currents are measured to three heat pump units, Brand A, Brand B and Brand C, in several villages which have completed the "*Coal-to-electricity*" programs. Ambient temperature is about -2 ~ -6 ℃. The operation voltages of the measurement nodes are near 220V when the heat pump units are switched off.
After the steady operation of the both Brand A and Brand B, the total harmonic distribution (THD) of the operation current is small. The measurement results are shown in Table 4.

Table 4. The starting dataand THD of Brand Aand Brand B

Type of the heat pumps	Brand A	Brand B
Maximum startup current / A	30.37	146.16
Maximum active power / kW	3.68	15.97
Minimum startup voltage / V	201.96	191.89
Duration of transient process / s	0.45	0.21
Ratio of maximum startup current to rated heat current / per unit	3.65	5.84
THD / %	10.2~10.8	10.5~10.9

Brand C is an ASHP unit with the variable-speed. In the process of starting, the soft start of the compressor speed conversion is applied, and the impact current is very small. The starting voltage is basically stable at about 220V. After the steady operation of the unit, its THD of the operation current is about 11.5~23.6%.

4. Simulation of rural distribution network with large scale heat pumps

4.1. Rural distribution network for simulation

The ratio of the maximum startup current to the rated heat current of Brand B is larger. Therefore Brand B is selected for the heat pump unit of the simulation. And the rurallow voltage distribution network of the corresponding village is shown in Figure 5. The main line where the node number is from 1 to 15and the line type is JKLYJ-120. The type of all the branch lines is JKLYJ-70. The parameters of the lines are shown in Table 5. The 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. The line length between two nodes is assumed to be 400 m for the purpose of simplicity. The power load of node 5, 15, B1-1, B1-3, B1-4, B2-1, B2-6, B3-2, B4-2, B5-2and B5-3 is assumed to be 3.1 kW, and the power load of node 10, B1-5, B2-4, B2-5, B3-1, B4-3and B5-1 is 4.6 kW. All users are basically evenly distributed in each phase.

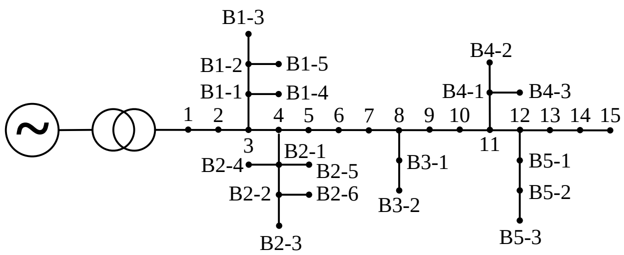

Figure 5. Rural distribution network diagram of a village

Table 5. Resistance and reactance of lines

Type of lines	JKLYJ-120	JKLYJ-70
Resistance of the one km length /(Ω/km)	0.27	0.297
Reactance of the one km length /(Ω/km)	0.46	0.315

4.2. Permeability of ASHP units

When the establishment of different simulation scenes is done, the permeability of the heat pump units, represented as r_{Per} in per unit, is considered.

$$r_{\mathrm{Per}} = P_{\mathrm{HP}} / P_{\mathrm{All}} = P_{\mathrm{HP}} / (P_{\mathrm{HP}} + P_{\mathrm{LV}}) \quad (4)$$

where P_{HP} is the total power of the steady operation of all the heat pump units in kW, P_{All} is the total power of the distribution network in kW, P_{LV} is the total power of the other ordinary load of the low voltage (LV) distribution network in kW.

4.3. Simulation of voltage sags

When the establishment of different simulation scenes is done, the permeability of the heat pump units, represented as r_{Per} in per unit, is considered.

When the number of the heat pump units connected to the distribution network is changed, i.e.r_{Per} being different, the startup influence of the units is simulated with the other constant LV loads. While r_{Per}= 0 with the load of all users in the LV distribution network, the voltage of node 15 is 215.7 V.

If the heat pump units are only connected to the node 15 with r_{Per}= 0.18, then the minimum residual voltage of node 15 is about 183.5V during the heat pump starting process, which is much lower than the threshold value of the voltage sags, 90% rated voltage, i.e. 198 V [3]. The sudden voltage drop must affect the operation of other electrical equipment.

If the heat pump units are only connected to the node 7 and node 15 with the same capacity and r_{Per}= 0.36, then the minimum residual voltage of node 15 is about 165.7V during the heat pump starting process, which is far below the threshold value, 198 V.

5. Conclusion

The voltage sags in a rural distribution network are simulated during the starting process of the heat pump units with different permeability of the units in this paper. With the increase of permeability of the fixed-speed heat pump units, the larger voltage sag may be caused during the heat pump starting process in the rural distribution network. The length and the section area of the distribution line affect the allowable permeability ratio of the heat pump units and the starting number of the units at the same time. When the heat pump units are installed in the rural area with the "*coal-to-electricity*" program, it is necessary to consider whether the new load demand of the heat pump units will be met according to the distribution transformer capacity and line parameters.With the increase of permeability of the variable-speed heat pump units, the current harmonic content will increase in the rural distribution network. It is necessary to take measures to suppress the harmonic content based on the actual situation of the distribution network.

Based on the typical feature and the types of the domestic heat pump units, the additional load forecast method of heat pump units is put forward. The power quality problems are analyzed by using the actual measurement data of the voltage sags and the harmonics of the heat pump units in the rural distribution network. The simulation results in the distribution network can be used as the reference for the further implementation of the "*Coal-to-electricity*" program.

6. Acknowledgments

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7. References

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