Impact of High Level of Renewable Energy Penetration on Inter-area Oscillation

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Abstract— **Many research projects have been focused on the impacts of each type of wind turbines on the stability of the power system. Due to the rapid increase in the penetration level of renewable energy and diverse power generation portfolios, it is vital to study the performance of the power system in presence of different renewable sources of energy. The focus of this paper is to study the small signal stability of a power system with high penetration level of wind and geothermal energy. The models of three commercially available wind turbines are used to investigate inter-area mode oscillations of a power system with renewable generators located in remote areas. Moreover, the performance of the power system with HVDC and HVAC interconnections is demonstrated. Simulations are carried out on a test power system using PSS/E software.**

Keywords-Damping; HVAC; HVDC; interarea oscillation; geothermal;renewable energy; small signal stability; wind turbine

I. INTRODUCTION

As the source of fossil energy decreases and demand for electricity increases, renewable energy gains increasing importance throughout the world, especially with the start of Greenhouse Gas (GHG) emission pricing approaching. Australia has a target of providing 20% generation from renewable sources by 2020. The serious zero-emission candidates are: hydro, wind, solar, biomass, geothermal and ocean. Because of the limited availability of the other resources, this target is believed to be achieved largely due to geothermal and wind energy. The utilization factors of intermittent renewable generation technologies are normally less than 50%. Thus, a large amount of renewable generation capacity will be required to achieve this target. Another problem for geothermal and wind power in Australia is their remote location. Overall, the impact of their penetration, with different transmission options, on power system stability needs to be taken into careful consideration.

There are three types of wind turbines that are widely used up to now: Induction Generator (IG), Doubly-Fed Induction Generator (DFIG) and direct drive permanent magnet synchronous generator (PMG) wind turbines (WTs). The impacts of large scale wind farm on power system electromechanical oscillations was first reported in [1]. However, only one model for variable speed wind turbine is used for the analysis. The power factor of WTs is equal to one and hence, the voltage control of the WTs is not considered in this paper.

An investigation on the impact of connecting large IG wind-farms to weak networks with long transmission lines on inter-area modes was conducted in [2]. IG wind turbines were used in the first stage of wind turbine technology development since the 1980's. This type of wind turbine has very little controllability and consumes reactive power. A popular type of variable-speed wind generators currently is the DFIG. In the literature, the impact of DFIGs on power system stability is well studied [3-7]. For voltage stability, the DFIG improves the voltage stability margin of both distribution and transmission level buses in the system. Therefore, large levels of wind generation could be connected without degrading the voltage stability of the system [5]. For small signal stability, the system is found to have both positive and negative impact with the increased penetration of DFIG, which can be identified by the eigenvalue sensitivity to inertia [3, 4]. Supplementary controllers for DFIG to damp system oscillations have been designed in [8-12]. The Power System Stabilizer (PSS) in DFIG with a rotor-side converter was used in [8] to damp the power system oscillation. However, the test system used in [8-12] were single machine infinitive bus (SMIB) system, which does not exhibit inter-area oscillations due to high penetration of DFIG. Miao et al. [10] claimed to be the first to study the DFIG penetration in a two area test system for inter-area oscillation analysis and proposed a wide-area feedback controller to effectively damp oscillation in [13].

In recent years, the use of direct drive permanent magnet synchronous generator (PMG) wind turbine is becoming more attractive, due to their high efficiency, absence of DC excitation systems and gear boxes. There are a number of research papers on PMG wind turbine modelling and controller design for fault ride through and voltage stability studies [14-16]. The small signal stability model of a PMG wind turbine is developed and verified in a SMIB test system in [17, 18]. Therefore, only oscillatory modes with frequency larger than 14 Hz, known as subsynchronous resonance (SSR), are considered and the impact of PMG wind turbine on the electromechanical oscillations is not studied.

Overall, the impacts of different types of wind turbines on power systems have been studied either as separate components or only with the SMIB system. This paper investigates the inter-area mode oscillations of a power system with high penetration level of wind and geothermal energy located at remote areas. Several scenarios of combination of wind turbines and geothermal power plant are studied by considering all types of commercially available wind turbines. First the impacts of individual types of wind farms and a large scale geothermal power plant on the small signal stability are examined for both HVAC and Line-Commutated Converters (LCC) HVDC interconnection options. Then, six different scenarios are defined in the generation portfolio and critical modes of the studied scenarios are identified. Simulation results demonstrate that increasing the penetration level of wind energy and wind speed has an impact on the small signal stability of the system.

The remaining sections of the paper is organised as follows. Section II provides background information on the small signal stability and wind turbine models. After describing the test case and its relevant details in Section III, section IV shows the simulation results for the test case. Section V concludes the paper.

II. BACKGROUND

A. Power system oscillation

Small signal stability is the ability of a power system to maintain synchronism when subjected to small disturbances, such as changes in power demand. The phenomenon is analysed using linear techniques based on valuable information about the natural dynamic characteristics of the system [19]

The most common approach for studying power system small signal stability is to use a linearized model of the power system.

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) \end{cases} \tag{1}$$

Where *x(t)* is the vector of state variables, *u(t)* is the vector of control inputs, and *A, B, C and D* are state, control, output and feed forward matrices, respectively.

Values of the scalar parameter λ that satisfy the following equations are known as eigenvalues of matrix *A*. Only complex eigenvalues ($\lambda_i = \alpha_i \pm j\beta_i$) are considered.

The frequency of oscillation in Hz, representing the actual damped frequency, is given by:

$$f_i = \frac{\beta_i}{2\pi} \tag{2}$$

For a particular eigenvalue λ_i, the damping ratio ζ_i is defined as:

$$\zeta_i = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \beta_i^2}} \tag{3}$$

The damping ratio determines the rate of decay of the amplitude of the oscillation. The system is only stable if damping ratios of all oscillation modes are positive. The larger the damping ratio is, the quicker the oscillation is damped.

Dominant state variables in a particular mode can be identified with the help of participation factors. *Participation factors* are combination of left and right eigenvectors of matrix A.

$$P = [P_1, P_2, \dots, P_n] \tag{4}$$

$$P_i = \begin{bmatrix} P_{1i} \\ P_{2i} \\ \vdots \\ P_{ni} \end{bmatrix} = \begin{bmatrix} \phi_{1i}\Psi_{i1} \\ \phi_{2i}\Psi_{i2} \\ \vdots \quad \vdots \\ \Phi_{ni}\Psi_{in} \end{bmatrix} \tag{5}$$

In general $P_{ki}=\phi_{ki}\psi_{ik}$; ϕ_{ki} is the k^{th} entry of the right eigenvector with i^{th} mode and ψ_{ik} is the k^{th} entry of left eigenvector associated with i^{th} mode. The participation factor is a measure of relative participation of the k^{th} state variable in the i^{th} mode.

Oscillation modes can be divided into electromechanical modes and control modes. One can determine that a mode is an electromechanical mode if the generator speed variables have the largest participation factor in this mode. Besides, participation factors also help to identify local modes (only one generator with significant participation factor) and inter-area modes (several inter-area generators with significant participation factors) [19].

B. Wind turbine models

1) IG wind turbine

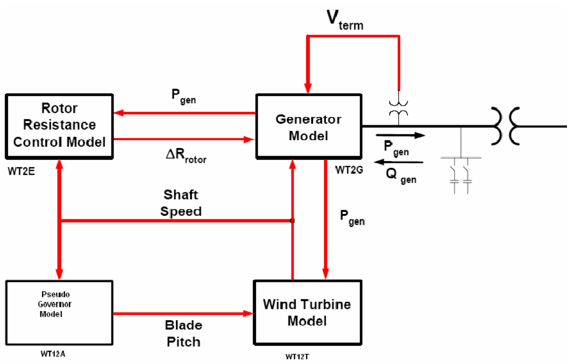

Figure 1. IG wind turbine connectivity diagram [20]

IG wind turbine is modelled as the fixed P and Q generator. This generator has a lagging power factor, i.e. the wind farm consumes reactive power. The controller model and WT parameters are taken from [20]. The diagram of IG WT connectivity is depicted in Figure 1.

2) DFIG wind turbine

DFIG wind turbine is modelled as the PV generator. This generator modelling comprises models as follows:

- Generator/converter model
- Electrical control model
- Mechanical control (wind turbine) model
- Pitch control model

The controller model and WT parameters are taken from [20]. The diagram of DFIG WT connectivity is depicted in Figure 2.

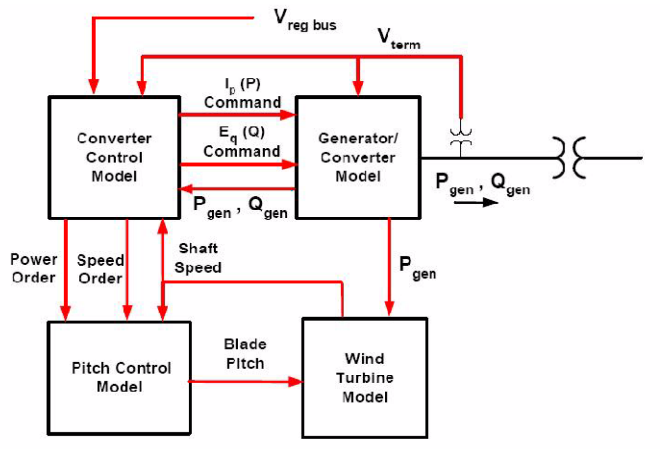

Figure 2. DFIG wind turbine connectivity diagram [20]

3) *PMG wind turbine*

PMG wind turbine is modelled as a PV generator. This generator modelling comprises models as follows:

- Power converter/generator model
- Electrical control model

The reactive control calculates the reactive current command for the bus voltage control option. Figure 3 shows the interaction between these models. The controller model and WT parameters are taken from [20].

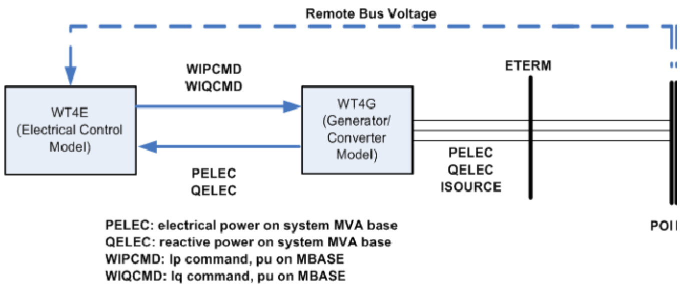

Figure 3. PMG wind turbine connectivity diagram [20]

III. SYSTEM DESCRIPTION

The study is carried out on a large power system consisting of 11 buses, 2634 MW load and 4 generators with total generation of 2,820MW. All the modelling details provided within the base set of data are retained and represented in the analysis. The system is depicted in Figure 4 below.

To simulate the situation of introducing a new renewable energy source to the power system, a geothermal power plant is connected to the grid by a 440km double circuit interconnection at bus 9. Three wind farms, which consist of 20% IG, 60% DFIG and 20% PMG WTs, are connected to the geothermal site through three 10km HVAC lines. The total capacity of new generators is 750MW, which is nearly 24% of the total demand. The penetration level of renewable sources of energy meets the target for renewable energy of Australian Government by 2020. The analysis performed is based on the information provided with regard to the existing and planned increases in total load, which are 2,634MW and 3,134MW, respectively.

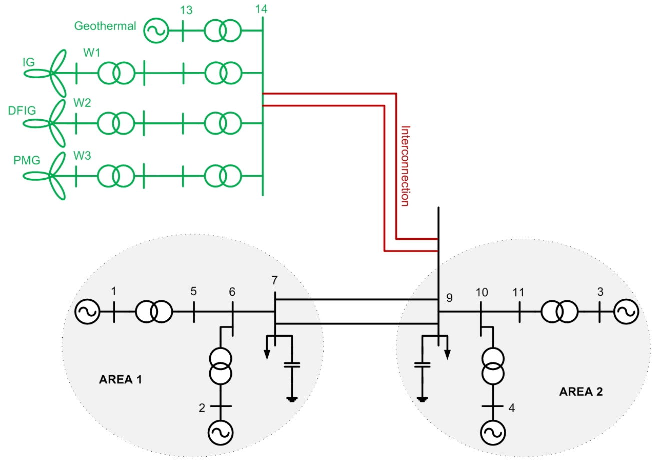

Figure 4. *Diagram of the modified two area test system*

IV. SMALL SIGNAL STABILITY

A. *Impacts of individual types of wind farm and geothermal power plant on the small signal stability*

To understand the behaviour of inter-area oscillation damping in the power system, impact of each type of renewable power plant on system stability is essential. The geothermal power plant is modelled as a synchronous machine. It is assumed that new added generators are 650MW geothermal and 100 MW wind. In the following subsections, three different types of wind turbines are separately considered and the small signal stability of the system in each scenario is investigated.

1) *IG wind turbine*

The eigenvalues of the inter-area mode between new generators and the existing system are shown in Table I.

TABLE I. INTER-AREA MODE BETWEEN NEW GENERATORS AND THE EXISTING SYSTEM

Case	Real	Image	Damping Ratio	Freq. (Hz)
Without WT	-0.0939	1.9725	0.0475	0.3139
With IG	-0.0321	1.1674	0.0275	0.1858

As can be seen from Table I, the introduction of IG WT reduces the damping ratio of the considered mode. As can be seen from Table I, the damping ratio of the system with presence of 100MW IG WT reduces. It has to be noted that damping can be improved by increasing the penetration level of wind energy.

Participation factors of generators in the considered mode are shown in Table II. With the IG WT, participation factors of existing generators are larger than those without IG WT. This could be one of the reasons that the frequency of the inter-area mode becomes smaller with the presence of IG WT, although the participation of this WT in this mode is very small (0.098).

TABLE II. PARTICIPATION FACTORS

Generators	Without WT	With WT
Geothermal	1	1
G2	0.3661	0.7014
G1	0.3823	0.6643
G4	0.1664	0.4883
G3	0.1557	0.4670
IG WT	NA	0.0945

2) *DFIG wind turbine*

The eigenvalues of the inter-area mode between new generators and the existing system are shown in Table III.

TABLE III. INTER-AREA MODE BETWEEN NEW GENERATORS AND THE EXISTING SYSTEM

Case	Real	Image	Damp. Ratio	Freq. (Hz)
Without WT	-0.0939	1.9725	0.0475	0.3139
With DFIG	-0.3281	3.0564	0.1067	0.4864

From Table III, it is found that the penetration of DFIG adds more damping of the inter-area oscillation to the system.

Dominant machines participating in this mode are the geothermal plant, and generators 1 and 2, which have participation factors of 1, 0.5 and 0.4 respectively. Participation factors of generators 3 and 4 in this inter-area mode are negligible. The participation factor of the DFIG WT is even smaller than that of the IG WT, which is 0.080 in comparison with 0.098. The frequency of the inter-area mode is increased significantly with the presence of DFIG WT, from 0.32Hz to 0.48Hz.

3) *PMG wind turbine*

The eigenvalue of the inter-area mode between new generators and the existing system are shown in Table IV.

TABLE IV. INTER-AREA MODE BETWEEN NEW GENERATORS AND THE EXISTING SYSTEM

Case	Real	Image	Damp. Ratio	Freq. (Hz)
Without WT	-0.0939	1.9725	0.0475	0.3139
With PMG	-0.2685	2.5430	0.1045	0.4047

It is clear from Table IV that the PMG WT helps to improve the inter-area oscillation damping of the system as considerably as the DFIG WT.

Although the result in [17] pointed out that the PMG WT add more damping to the system with or without the controllers, there were only SSR oscillations in their test system. The impacts of increasing penetration of PMG WT on inter-area oscillation have not been either considered in the literature. In this section, the output power of PMG is increased to study this problem.

The impacts of increased penetration from 0MW to 500MW of PMG WT on the inter-area mode are shown in Figure 5. The total capacity of new generators is maintained at 750MW. Figure 5 shows that the increase in penetration of the PMG WT slightly improves the oscillation damping of the system.

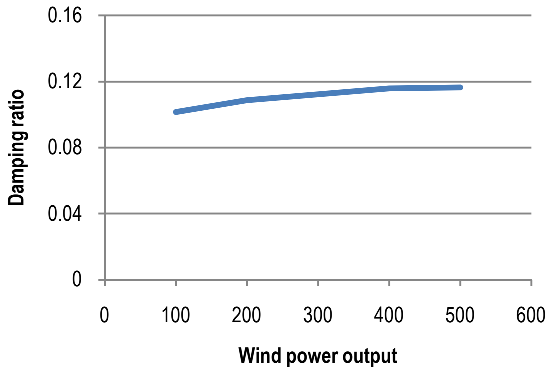

Figure 5. Impacts of increased penetration of PMG WT on inter-area mode

B. *Impacts of the combination of renewable sources on power system small signal stability with full capacity WTs*

1) *Scenario description*

Six different cases are analysed. The description of each case is provided below:

- Case A constitutes the case when only the 750MW geothermal power plant is connected to the system by an HVAC line. The geothermal generator is a conventional round rotor synchronous machine of 900MVA rating.
- Case B constitutes the case when a 500MW geothermal power plant and 250MW wind farms are connected to the system by an HVAC line.
- Case C constitutes the case when a 250MW geothermal power plant and 500MW wind farms are connected to the system by an HVAC line.
- The HVAC line in cases A, B, C replaced by a Line Commutated Converter (LCC) HVDC line is referred to cases D, E, F, respectively.

For all the cases, the participation rate of IG, DFIG and PMG are 20%, 60% and 20% respectively.

2) *Eigenvalue analysis*

Detailed eigenvalue analysis is only presented for cases B and E, since the behaviour of power system with synchronous generators is well studied in the literature.

There are two local modes and one inter-area mode for the original system. Table V shows the details of all electromechanical modes of the system when a combination of renewable generators is installed.

As can be seen from Table V, the new group of renewable generators has a negligible impact on the existing electromechanical modes of the system. However, it can be expected that new generators installed cause more oscillations in the system. Three new modes appear for both cases. Mode 5 is the inter-area oscillation of the geothermal power plant with the wind farms. Only wind farms are found to participate in mode 6. In case B, mode 4 is the inter-area oscillation of geothermal and area 1 generators, of which the participation factors are not very high. In case E, the new generators are connected to the system by an HVDC link, therefore this mode becomes the inter-area oscillation between geothermal and wind power plants. Generators in area 1 also participate in this mode but with minimal participation factors.

TABLE V. ELECTROMECHANICAL MODES OF THE SYSTEM

Mode	Case (Frequency f in Hz, Damping ratio ζ)		
	Without renewable	*Case B*	*Case E*
1	-0.5078±j3.5619 (f=0.57, ζ=0.14)	-0.5717±j3.6518 (f=0.57, ζ=0.14)	-0.5456±j3.5973 (f=0.57, ζ=0.15)
2	-1.9515±j7.3467 (f=1.2, ζ=0.26)	-1.6775±j6.8886 (f=1.1, ζ=0.24)	-1.7793±j6.9303 (f=1.1, ζ=0.25)
3	-1.7504±j6.9262 (f=1.1, ζ=0.25)	-1.6906±j6.6838 (f=1.1, ζ=0.25)	-2.0198±j6.7891 (f=1.1, ζ=0.29)
4	NA	-0.38007±j2.607 (f=0.41, ζ=0.14)	-0.33±j0.8158 (f=0.13, ζ=0.37)
5	NA	-1.3515±j5.6263 (f=0.9, ζ=0.23)	-1.8309±j4.7658 (f=0.76, ζ=0.36)
6	NA	-1.5912±j3.4538 (f=0.55, ζ=0.42)	-1.6056±j3.0401 (f=0.48, ζ=0.47)

All the damping ratios of the system oscillations for case E are larger than the ones in case B. Therefore, HVDC is the better option to connect the remote renewable energy source compared to HVAC in terms of small signal stability.

3) Impact of wind penetration level on the inter-area oscillation

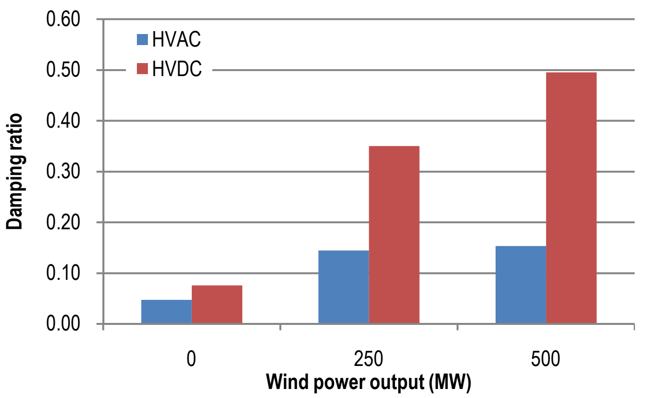

Figure 6. Impacts of increased scale of wind energy on inter-area modes

Figure 6 shows the damping ratios of mode 4 for 4 cases. It can be seen that the penetration of wind turbines improves the small signal stability of the system with both transmission options.

As expected, the increase in wind penetration for both interconnection scenarios helps to improve the damping ratio of the inter-area mode significantly. With HVDC, the damping ratio of this oscillation increases more sharply compared to HVAC.

4) Impacts of increased wind speed on the inter-area oscillation

In general, the output power of a WT is normally equal to 20-40% of its full capacity. The reasons are availability of wind and wind speed. In this section, the impact of increased wind speed on the inter-area oscillation is investigated. The increase in wind speed is represented by the increase in output power (in pu with the machine base). Detailed eigenvalue analysis is conducted for cases C and F with the output power of the three wind farms increasing from 25 to 100% of the rated power. Modes 3 and 4 are not sensitive to the change in wind speed. It could be expected because participation factors of WTs in those modes are negligible. As stated above, mode 5 is the inter-area mode between the geothermal generator and wind farms. Therefore, only the damping ratio of this mode is considered. The relationship between wind speed and the damping behaviour of mode 5 is shown in Figure 7.

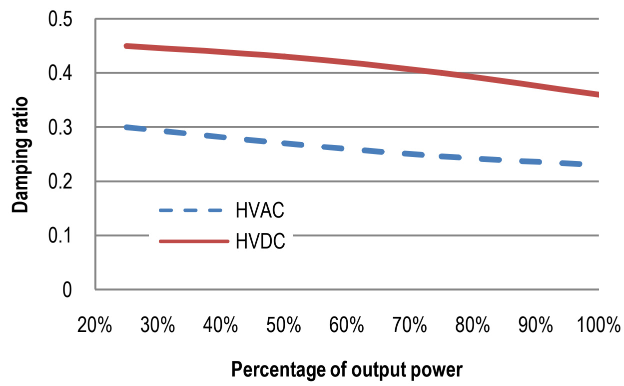

Figure 7. Impact of wind speed on the inter-area mode of new generators

For IG, at low wind speed condition, it is expected that the system stability becomes worse due to the large amount of reactive power consumption. On the other hand, the controllability and built-in reactive compensation of DFIG and PMG help to stabilize the system when wind speed is low. With the specific combination of WTs considered in this study, the IG wind farm (with 20% of total wind farm capacity) has a smaller impact on the system oscillation damping behaviour compared to the other two types of WTs.

TABLE VI. EGEINVALUES FOR CASE B AND CASE C WITH THE SAME OUTPUT POWER OF WINDFARM

Mode	Damping ratio	
	Case B	*Case C*
5	-1.3515±j5.6263 (f=0.9, ζ=0.233)	-1.4168 ±j 5.5868 (f=0.9, ζ= 0.246)

Table VI gives the damping ratio of mode 5 for case B (250 MW wind farm at 100% power output rate) and case C with

(500MW wind at 50% power output rate). The actual output powers of wind farm and geothermal plant in these two scenarios are 250MW and 500MW, respectively.

As can be seen from the Table VI, with the same output power, the system with wind farm operated at full rate (case B) is less stable than that at lower rate (case C). Therefore, from small signal stability point of view, having more wind farm with low wind speed is of beneficial operation.

For HVDC result, the same oscillation behaviour is observed.

V. Conclusions

In this paper, the impact of different renewable energy sources integration to the power system was investigated. The penetration of renewable generators (wind and geothermal) has negligible impacts on the damping of existing electromechanical modes of the test system. However, the new generators induce several oscillatory modes. The analysis conducted indicates that the new inter-area mode is more stable when the penetration level of wind farm is increased. It has to be noted that the total output power of new generators remains unchanged.

At a fixed rated power of wind farms, the increase in wind power dispatch caused by the increase in wind speed reduces the damping ratio of the inter-area mode. It has been observed that increasing the penetration level of PMG WT slightly improves the damping of inter-area mode. Also in terms of small signal stability for all scenarios, LCC HVDC is found to be a better option than those with HVAC.

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