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A Study of Distributed Generation System Characteristics and Protective Load Control Strategy

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Abstract- **Due to the smaller inertia feature of a Wind Turbine (WT) involved Distributed Generation System (DGS), the WT's induction generator are more vulnerable to frequency and voltage disturbances. Therefore the study investigates the DGS characteristics respectively from power plants, i.e. WTs and load. Two kinds of wind turbines: Doubly-fed Induction Generator (DFIG) and Fixed-speed Wind Turbine (FSWT) are compared in this study. A conventional power system protective scheme may not response promptly, which could lead an undesired disconnection of WTs for the turbine protection purpose. Consequently a fast protective load control strategy to such a DGS is studied. In order to implement such a strategy a communication system associated with a DGS is configured. With this strategy a precise and prompt load shedding operation can be performed to ensure the stability of a DGS and WTs. The impacts of load characteristics are analyzed and utilized in the fast control strategy. Subsequently a case study is presented to demonstrate the theoretical investigations and analyses.**

Index Terms**—Wind Turbine (WT), Combined Heat and Power (CHP), Distributed Generation System (DGS), Doubly-fed Induction Generator (DFIG), Fixed-speed Wind Turbine (FSWT), load shedding, Ethernet.**

I. Introduction

With the fast development of the renewable energy in power industry, the monitoring, control and protection of a Distributed Generation System (DGS) with Wind Turbines (WT) have attracted significant attentions. A DGS with renewable sources such as WTs and solar panels is distinct from a conventional power system. The renewable generation units make a DGS to be increasingly distributed, decentralized and deregulated. Moreover the increasing involvement of power electronics devices in DGS has changed the power system characteristics, for example, the dependency feature between power and frequency may become less significant than before. Some literature surveys reveal that the recent large scale system blackouts are increasingly due to voltage collapses caused by reactive power deficiency, rather than frequency drops [1]. Additionally induction generator based fixed-speed wind turbine (FSWT) and doubly-fed induction generator wind turbine (DFIG) have different characteristics, when different type of WTs are integrated into a DGS, the DGS presents different properties. Therefore the controlling and protection schemes of operating a DGS with WTs, for instance load shedding strategies, should be adaptive to the new properties of the systems.

Due to the smaller inertia, a wind generator is more vulnerable to frequency and voltage disturbances. However a conventional system protective scheme, such as low frequency load shedding or low voltage load shedding, may not response promptly and could lead an undesired disconnection of WTs by the turbine protection. Consequently a fast protective strategy to such a DGS is necessary to avoid the loss of wind power generation. In this study the response time requirements of a load control strategy are investigated and elaborated. In order to implement such a strategy an associated communication system to a DGS is indispensable. With this communication system, a DGS is monitored and controlled by the gathered real-time information. Accordingly the latencies of the protective operations can satisfy IEC61850 standards.

In this paper, Section II introduces distributed generation system's characteristics, which include load characteristics, the induction generator based FSWT and DFIG features. Section III describes a communication system associated with a DGS. In Section IV, an Ethernet communication network based protective load control strategy is proposed. Section V demonstrates the effectiveness of the protective load control strategy by a case study. Conclusions are drawn in Section VI.

II. Distributed Generation System Characteristics

In this section the DGS is characterized with FSWTs, DFIGs and CHPs as DG units. The load characteristics are also studied. The dynamic analyses on WTs' behaviour are presented.

A. Load characteristics

The load characteristics have a significant influence on system stability. Regarding load shedding operations, the response speed of a DGS is critically related with the characteristics of the loads to be shed and the loads to be kept in a DGS. In this part, the load characteristics are presented.

The static model of loads may be represented as (1) [2].

$$\begin{aligned} P &= P_0(\bar{V})^a(1+K_{pf}\Delta f) \\ Q &= Q_0(\bar{V})^b(1+K_{qf}\Delta f) \end{aligned} \tag{1}$$

Where $\bar{V} = V/V_0$, a= dP/dV, (0.5~1.8); b= dQ/dV, (1.5~6); $K_{pf} = dP/df$, (0 ~3.0); $K_{qf} = dQ/df$, (-2.0~0); P_0, Q_0, V_0 are respectively the rated active power, reactive power and rated voltage.

Figs. 1 and 2 clearly show the effects of different dP/dV, dQ/dV. Naturally, the greater dP/dV, dQ/dV, the more sensitive of the active power and reactive power consumption to voltage and frequency. If voltage drops, the greater the *dP/dV*, *dQ/dV* are, the more P and Q reduction are.

Figs. 3 and 4 show the impact of K_{pf} , K_{qf} , while the other two parameters, *dP/dV* and *dQ/dV*, are set as 1.0 and 2.0 respectively as most commonly accepted static load model [2]. It is obvious that when the frequency varies, a load with the greater *dP/df*, *|dQ/df|* has the more significant influences on P and Q.

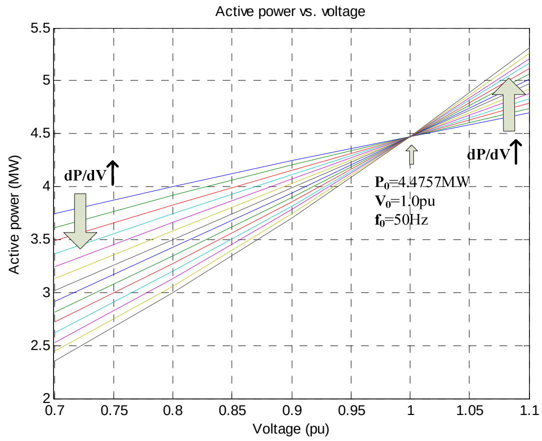

Fig.1. Load active power vs. voltage at various *dP/dV*.

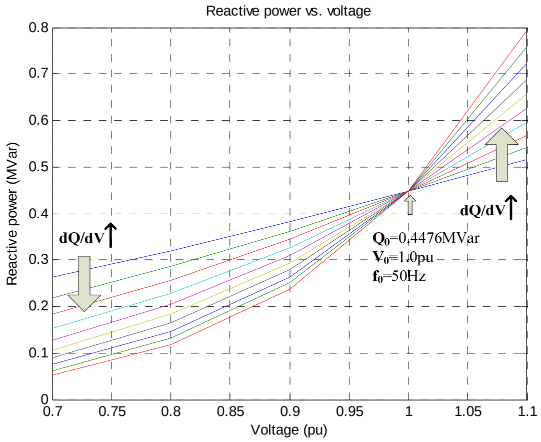

Fig.2. Load reactive power vs. voltage at various *dQ/dV*.

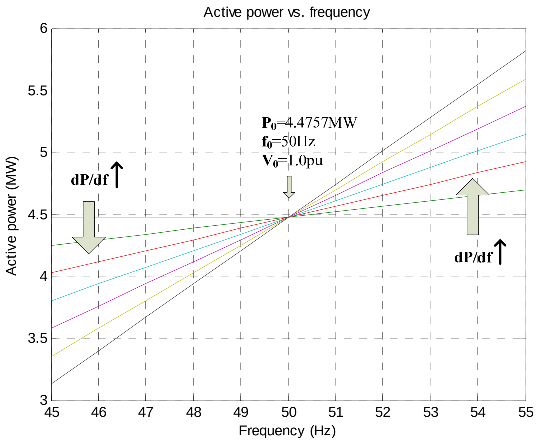

Fig.3. Load active power vs. frequency at varoius *dP/df*.

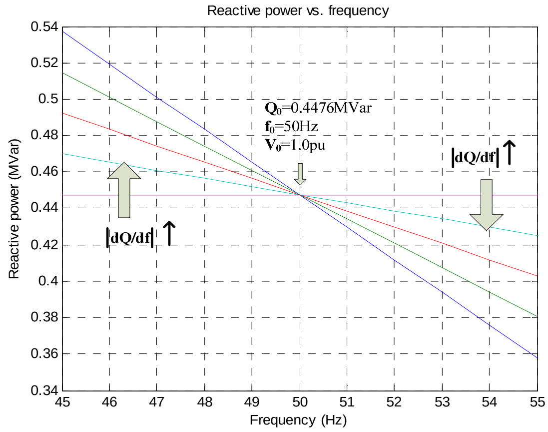

Fig.4. Load reactive power vs. frequency at various *dQ/df*.

The features of the load are considered in the load shedding scheme in the later part of the paper.

B. FSWT characteristics

The specification of a FSWT is given in Table I, its Cp (the power coefficient) curve and power (pu) vs. wind speed (m/s) curve are presented in Fig. 5 and 6 respectively.

TABLE I
A FSWT SPECIFICATION

Rated Power	600kW
Rated Voltage	0.69kV
Radium	21m
Vm	30rpm
Gear Ratio	1:50.5

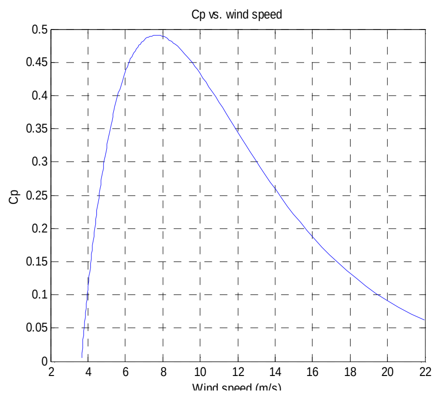

Fig. 5. A FSWT Cp curve.

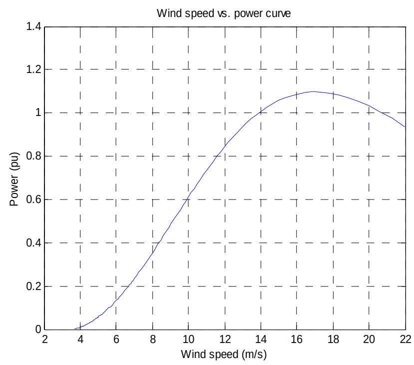

Fig. 6. A FSWT power curve.

C. DFIG characteristics

The specification of a DFIG is given in Table II, its Cp curve vs. λ (the ratio of the rotor blade tip) and power (pu) vs. wind speed (m/s) curve are illustrated in Figs. 7 and 8 respectively.

TABLE II
A DFIG SPECIFICATION

Rated Power	1.8MW
Rated Voltage	0.69kV
Radium	40m
Vm	1500rpm
Gear Ratio	1:100.5

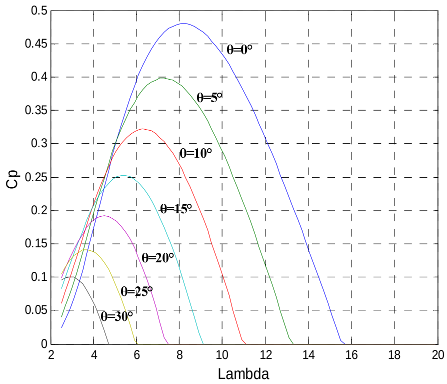

Fig. 7. A DFIG Cp curve.

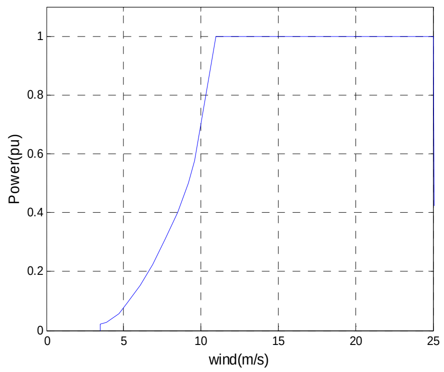

Fig. 8. A DFIG power curve.

III. AN ASSOCIATED ETHERNET COMMUNICATION SYSTEM FOR A DGS

According to IEC61850, Ethernet Communication system is determined to access to and associate with a power system for monitoring, control and protection. Therefore in this study, an Ethernet communication network is utilized for a DGS and is simulated by OPNET, as shown in Fig. 9.

Each WT controller, bay controller or relay IED is assigned a distinct IP address and is represented by a communication node. The transmission line of the Ethernet network in this study is decided as 100BaseT duplex link, which represents an Ethernet connection operating at 100Mbps. With this configuration, an Ethernet communication system can provide ETE (End-To-End) Delay in an order of millisecond, as shown in Fig. 10. The detailed deployment of a power system associated Ethernet network has been introduced in [3]. Fig. 11 gives the Ethernet channel utilization in percentage. Fig. 12 illustrates the Ethernet channel point-to-point throughput in packets/second.

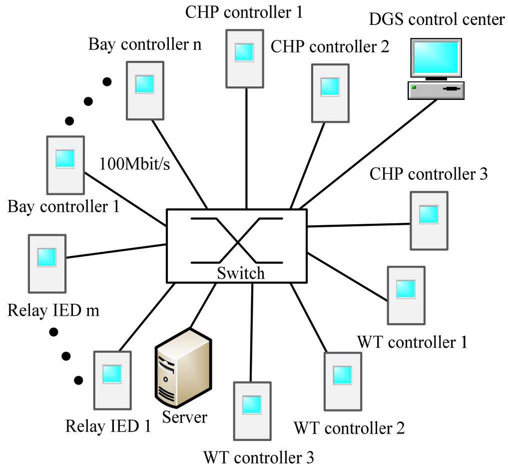

Fig. 9 A communication network.

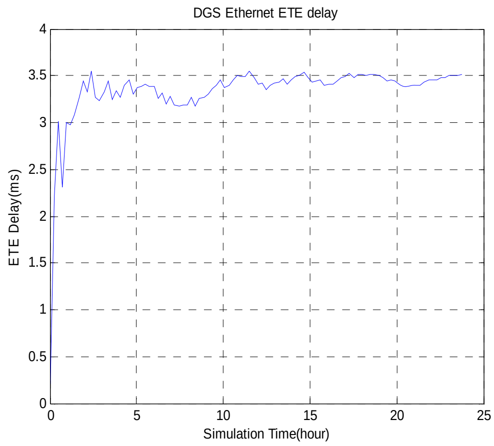

Fig. 10 A DGS associated Ethernet End-To-End delay.

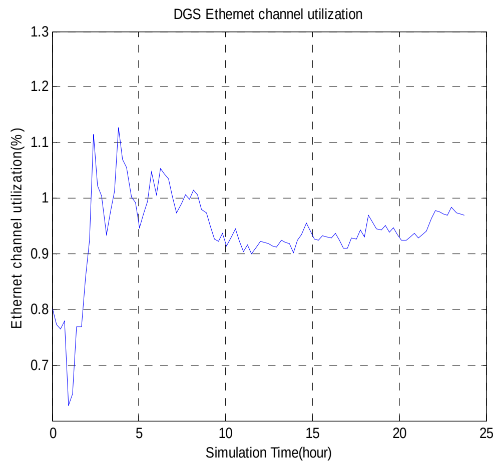

Fig. 11 A DGS associated Ethernet channel utilization.

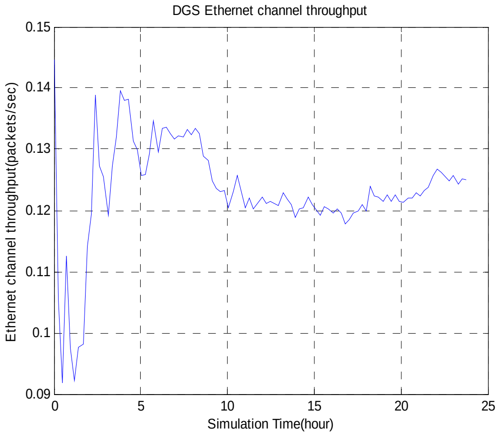

Fig. 12 A DGS associated Ethernet channel throughput.

IV. An Ethernet Based Protective Load Control Strategy

Based on the assist of the Ethernet communication system, the protective load control strategy is proposed in this section.

It mainly includes three key aspects: to determine the total amount of load to be shed, to select the load to be shed, and to decide the execution time of load shedding operation. The three aspects are addressed respectively as follows.

A. *The total amount of Load to be shed*

When load shedding operation is unavoidable under some conditions, for instance a DGS is islanded after a fault in grid side and the DGS generation is deficient, the total amount of load to be shed (P_{shed}) is decided by the deficiency of the DGS generation, which can be determined with the assistance of an associated communication network. Once a DGS islanding status is detected, the computation of P_{shed} is activated simultaneously, which is the difference between the CHPs reservation (P_{resv}), and the power flow (P_{flow}) from the grid to the DGS right before the islanding, as formulated by (2).

$$P_{shed} = P_{flow} - P_{resv} \quad (2)$$

B. *The selection of load to be shed*

After the determination of total amount of load to be shed, the sequence of load shedding operation has to be decided by checking a prescribed look-up-table. The sequence look-up-table is based on two principles: the first is the customers' payments, the more a customer pays, the more important the customer's load is, then the later the load may be shed, the second is the load characteristics, which is based on the analysis in Section II part A, the load which is more sensitive to system voltage or frequency, the later the load may be shed.

C. *The execution time of load shedding operation*

The execution time of any protective load control operations may directly impact the DGS and the WTs voltage and frequency which have to meet the requirement of the power system codes. The wind turbine technical regulation, which is briefly explained by Table III [4], is dominantly considered in this study.

TABLE III
Wind Plant Operation Requirements

Protection functions	Settings	Function time
Overvoltage (step 3)	1.2pu	5-100ms
Overvoltage (step 2)	1.1pu	200ms
Overvoltage (step 1)	1.06pu	60s
Undervoltage	0.9pu	10-60s
Overfrequency	52Hz(1.04pu)	200ms
Underfrequency	47Hz(0.94pu)	200ms

V. A Case Study

A simplified case based on Støvring local DGS in Denmark is studied. This study compares the cases of FSWT connected DGS and DFIG connected DGS characteristics. Fig. 13 and 14 respectively show the DGS with 3 Fixed-speed wind turbines (FSWT) and with an equivalent Doubly-fed induction generator wind turbine (DFIG). The FSWT and DFIG specifications are given in Section II part B and C.

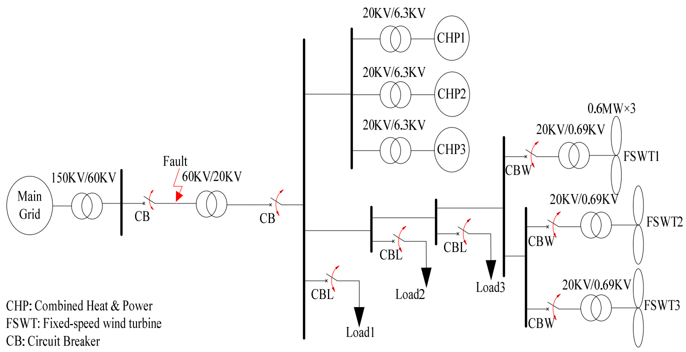

Fig. 13 A DGS with 3 FSWTs.

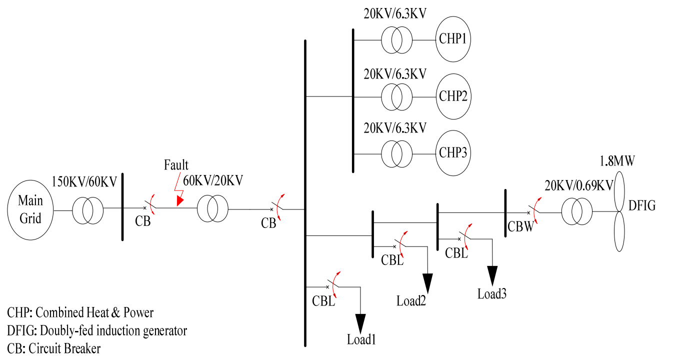

Fig. 14 A DGS with 1 DFIG.

A. *The scenario of a case study*

In the studied scenario, a three-phase-to-ground fault occurs at 8s, the DGS is islanded at 8.15s by opening the CBs in Figs. 13 and 14. Assuming the WTs are all under rated wind speed, thus they all generate rated power.

The DGS residential loads, commercial and industry loads are represented as 3 distributed load groups, as specified in Table IV. The studied protective load control operations are executed on Load 1, which is further divided into 8 loads, whose details are listed in Table V.

TABLE IV
DISTRIBUTED LOAD GROUPS ACTIVE POWER AND REACTIVE POWER

Load group	Rated active power (MW)	Rated reactive power (MVar)
Load 1	12.1752	3.6528
Load 2	0.3687	0.0681
Load 3	0.3687	0.0681

TABLE V
LOAD 1'S CHARACTERISTICS

Load No In Load 1	Rated active power (MW)	Rated reactive power (MVar)	dP/dV	dQ/dV	dP/df	dQ/df
1-1	1.5219	0.4566	0.5	1.5	0.0	0.0
1-2	1.5219	0.4566	1.8	1.5	3.0	0.0
1-3	1.5219	0.4566	0.5	1.5	0.0	0.0
1-4	1.5219	0.4566	0.5	6.0	0.0	-2.0
1-5	1.5219	0.4566	1.0	2.0	1.5	-1.0
1-6	1.5219	0.4566	1.0	2.0	1.5	-1.0
1-7	1.5219	0.4566	1.0	2.0	1.5	-1.0
1-8	1.5219	0.4566	1.0	2.0	1.5	-1.0

In this scenario, based on (2) calculation, only one load in Table V is necessary to be shed. Assuming payments of the 8 loads are on the same priority level here, therefore the load shedding operation priority is only based on their technical features. The process duration of load shedding operation includes the load shedding relays control signals transmission time latency (Ethernet ETE delay) and the load shedding circuit breakers operation time.

B. Simulation results

1) The cases of Figs 15 and 16 focus on the investigations on the impacts of load shedding on the loads with different dP/dV and dP/df properties.

Load 1-1 is with the smallest dP/dV, dP/df values, while Load 1-2 is with the greatest dP/dV, dP/df values [2]. With the assist of communication system the load shedding operation may be executed before 8.65s to keep the DGS stable, yet without the communication system the operation may be traditionally initiated until voltage or frequency drop down to a lower limit, thus can be seconds after the islanding, here given 9.25s as a compared late load shedding time.

Fig. 15 presents the voltage comparison between the FSWT connected DGS and the DFIG connected DGS. For the DFIG DGS case, the voltage always satisfies the requirement, no matter Load 1-1 or 1-2 is shed at 8.65s, or even the load shedding operation is at 9.25s. However, for the FSWT DGS case, the FSWT loses stability when the load shedding is operated at 9.25s.

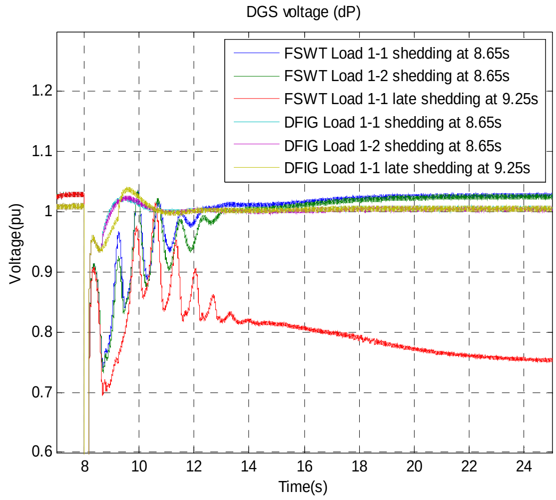

Fig. 15 Voltage variations of load shedding on the loads with different dP/dV, dP/df characteristics.

Fig. 16 presents the frequency comparison between the FSWT connected DGS and the DFIG connected DGS. The DFIG frequency can be ultimately stabilized in the normal operation range, no matter Load 1-1 or 1-2 being shed or late operation, but during the transient process right after the islanding, only load shedding on Load 1-1 can satisfy the frequency requirement according to Table III, as its duration of underfrequency process is around 180ms. However, the FSWT frequency varies in a bigger range than the DFIG. Only a prompt load shedding can lead the FSWT meet the frequency requirement [4].

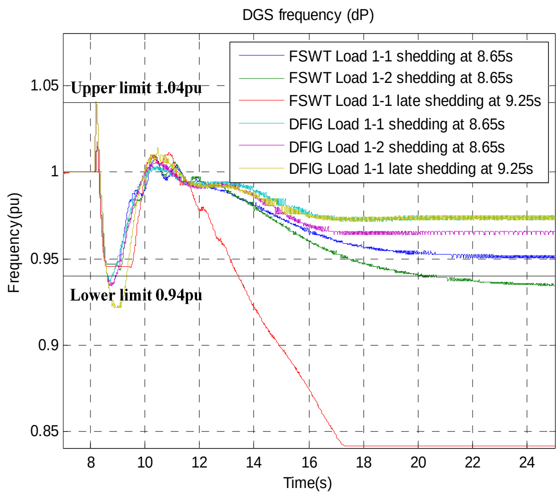

Fig. 16 Frequency variations of load shedding on the loads with different dP/dV, dP/df characteristics.

2) The cases of Figs 17 and 18 focus on the investigations on the impacts of load shedding on the loads with different dQ/dV and |*dQ/df*| properties.

Load 1-3 is with the smallest dQ/dV, |*dQ/df*| values, while Load 1-4 is with the greatest dQ/dV, |*dQ/df*| values [2]. With the assist of communication system the load shedding operation may be executed before 8.56s to keep the DGS stable, yet without the communication system the operation may be traditionally initiated until voltage or frequency drop down to a lower limit, thus can be seconds after the islanding, here given 8.75s as a compared late load shedding time.

Fig. 17 presents the voltage comparison between the FSWT connected DGS and the DFIG connected DGS. For both the DFIG DGS case and the FSWT DGS case, the voltage always satisfies the requirement [4], no matter Load 1-3 or 1-4 being shed, or even late load shedding operation.

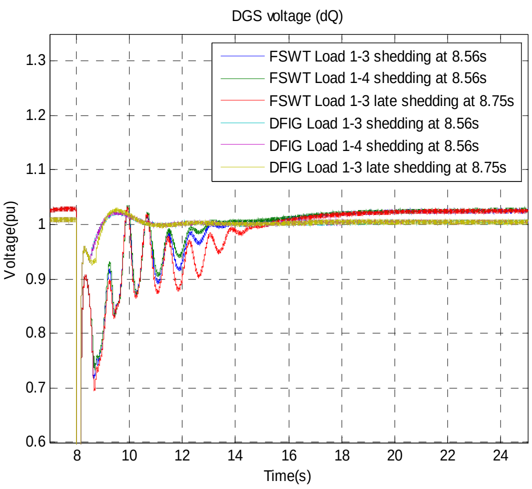

Fig. 17 Voltage variations of load shedding on the loads with different dQ/dV, |*dQ/df*| characteristics.

Fig. 18 presents the frequency comparison between the FSWT connected DGS and the DFIG connected DGS. The DFIG frequency can all be ultimately stable in the normal operation range, no matter Load 1-3 or 1-4 being shed or late operation, but during the transient process right after the islanding, only load shedding on Load 1-3 and 1-4 can satisfy the regulation on frequency requirement, as their duration of underfrequency is both around 180ms. However, the FSWT frequency is not able to meet the requirement at all.

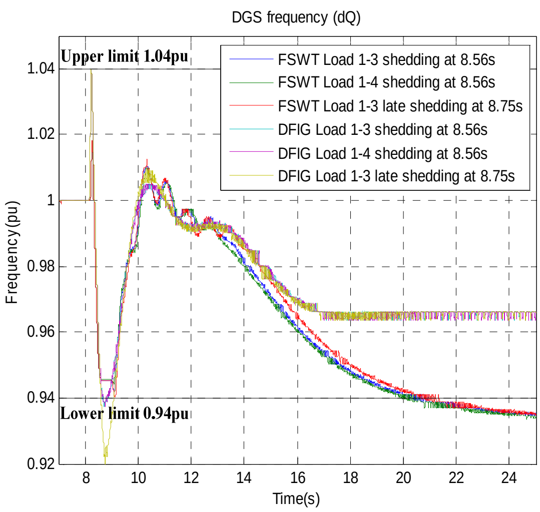

Fig. 18 Frequency variations of load shedding on the loads with different dQ/dV, |*dQ/df*| characteristics.

C. Discussions

Regarding the load shedding operations, the loads with the smallest dP/dV, dP/df, dQ/dV, |*dQ/df*| values are on the highest priority to be shed. Furthermore the load shedding operation execution time is critical to a WTs connected DGS, due to the WTs' sensitivity to disturbances. The earlier the load shedding execution time is, the more secure the WT operation is.

In terms of the comparison of FSWT and DFIG connected DGS, the FSWT DGS is more sensitive on load shedding with different load characteristics than the DFIG DGS. Furthermore the load shedding operation of FSWT DGS is more time critical than DFIG DGS.

Consequently, only prompt load shedding operations by an assist of a communication network is ideal for a wind power involved DGS. Any extra execution delay may cause a WT lose stability to lead an undesired cutting off.

VI. Conclusions

This study investigates the characteristics of a distributed generation system connecting wind turbines, which includes loads and WTs characteristics. A communication technology based protective load control strategy for a WT DGS is proposed in this study in order to satisfy the wind power plants regulations. A case study is utilized to compare the impacts of load shedding operations on the loads with different load characteristics, different load shedding operation execution time. This study also includes the comparison of two kinds of WTs connected DGS: FSWT and DFIG. Simulation results reveal that the FSWT DGS is more sensitive on load shedding with different load characteristics than the DFIG DGS. Furthermore the load shedding operation of FSWT DGS is more time critical than DFIG DGS.

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