# Distribution Network Characterization for Ancillary Service Provision: Frequency Response through Voltage Control

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***Abstract*—The rising share of distributed generation (DG) in the power system results in reduced inertia and larger frequency deviations following power imbalance. Balancing efforts of transmission system will require increasing coordination of distribution networks. This paper analyses impact of different characteristics of Low Voltage (LV) networks on its power consumption when varying voltage at point of common coupling in order to support frequency containment of transmission system. Frequency support is delivered by adapting the LV grid voltage to shape power consumption of voltage-dependant loads. It enables the use of voltage as a trigger for active power control of l voltage-dependant loads without the need for additional communication and frequency measurement. The Smart Transformer allows a fast control of voltage amplitude, and consequently, power consumption of LV grid without affecting medium voltage grid. Different network characteristics were analysed to determine networks most suitable for providing frequency support through voltage control.**

***Index Terms*—Load voltage sensitivity, frequency regulation, load control, demand response.**

## I. INTRODUCTION

In the recent years, power systems have been experiencing a shift from classical dispatchable units to intermittent, power-electronics interfaced renewables [1]. Faster and larger frequency transients that may endanger system stability, such as frequency events in continental Europe [2] and the UK [3], have been occurring more often in power systems with low inertia [4], [5]. Providing frequency support through controlling voltage dependent loads has drawn increasing attention in power research area. Power consumption of voltage dependent loads is adapted to desired level by varying network voltage. The advantages of this method include:
(i) reduced communication infrastructure, because voltage acts as a trigger for power control
(ii) utilising distribution networks and microgrid resources in frequency balancing efforts of transmission system
(iii) providing a short-term flexibility for balancing purposes and in some cases, soft load reduction can be used instead of firm load shedding.

Conservation Voltage Reduction (CVR) [6] is the intentional, continues decrease in customer voltages and has been used by utilities for at least 40 years to achieve energy or demand reduction [7]. However, operating over a wide area close to voltage limits can put some customers in risk of under voltage conditions [8]. Customer load active system services project [9], [10] proposed a novel load management scheme that provides flexibility for balancing purposes to the transmission system operator (TSO) without direct engagement with customers. Instead, when instructed, distribution network operators (DNOs), use existing on-load tap changers (OLTC) to control voltage supplied to distribution network and decrease power demand. Because of slow response time, OLTCs are more suitable for secondary or tertiary frequency response [11]. Dynamic Frequency Control Support [12]–[14] based on Load Voltage Sensitivity is a fast-acting method of short-term frequency support to isolated power system that controls the loads through variation in grid voltage. Grid voltage is controlled through Automatic Voltage Regulators, which are implemented to synchronous generators. This approach is limited to small power systems because changing output voltage of generators does not reduce voltage of remote loads. Primary frequency regulation using high-voltage direct current (HVDC) terminals to control voltage dependent loads is described in [11] and [15]. Traditionally, HVDC links provided frequency support through power flow control between two areas [16]. It results in reduction of power deviation in the area affected by the disturbance, but also causes power imbalance leading to frequency deviation in the second area. In power systems with low inertia it could result in frequency incidents. Proposed method overcomes challenge of power imbalance in healthy area by regulating voltage at HVDC terminals to change power consumption of voltage dependent loads in the unaffected area.

Smart Transformer [17] is a power electronics transformer. It enables control of voltage of low voltage grid without affecting medium grid voltage. Because of its fast response time, ST can provide primary frequency response [18]. In response to frequency deviation, ST can be used to control voltage at distribution network, and consequently, change power consumption of loads. To ensure desired power change,

Robowska, M., Syed, M., Burt, G., & Xu, Y. (2023). Distribution network characterization for ancillary service provision: frequency response through voltage control. In 2022 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia) (pp. 275-279).
(2022 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia)). IEEE.

load sensitivity (active and reactive power response) to voltage variations is calculated in advance using OLLI algorithm [19]. It was proved that 20% of ST-controlled load can reduce frequency nadir by 100 mHz [18] and avoid load shedding following a severe power imbalance [20]. However, amount of total power that can be provided to transmission system depends on the type of distribution network. Due to high cost, STs should be placed in an optimal location to support system stability.

This paper investigates impact of different network characteristics on consumed power while varying voltage in distribution network to identify types of distribution networks that are most suitable to support primary frequency response. The analysed parameters include: line resistances and 4 different load types; residential, commercial, industrial and mixed load.

The remainder of this paper is structured as follows: Section II presents background and previous work, the test system utilized for characterizing the networks response is detailed in Section III, network characteristics are evaluated in Section IV and Section V concludes the paper.

## II. NETWORK CHARACTERIZATION

Understanding the active and reactive power response of aggregate load to voltage changes is essential for control of grids with high demand variability and penetration of renewable energy sources. There are three methods of estimating load characteristics [21]: component based, measurement based and combination of component based and measurement based. Component based approach identifies the aggregated load. In [22], theory of fuzzy C means clustering is used to draw load characteristics based on network tropology, load control measurement system and substation power information. Measurement-based approaches utilise either uninduced [23] variation in grid voltage or apply a small voltage change [24] to measure active and reactive power consumption. Load modelling considering impact of distributed generation is presented in [25]. The On-Line Load Identification [20] concept can estimate in real time the load sensitivity to voltage variations by determining exponential static characteristics of aggregated load. The On-Line Load Identification considering impact of distributed generation of apparent voltage sensitivity on the load is discussed in [21]. This paper aims to identify general characteristics of networks that are most suitable for supporting primary frequency response through voltage control.

## III. TEST SYSTEM

In this section, the test system utilized for characterizing frequency support response is presented. The entire test system is modeled in digital real time simulator from RTDS Technologies. The system is simulated at a time-step of 50 $\mu$s. The following sub-sections detail the network and the constituent components.

### A. Network Model

A 7-bus radial distribution network is chosen for conducting the network characterization as shown in Fig. 1. The 12.66 kV distribution network is connected to the 33 kV grid by means of an on load tap changer transformer. The OLTC is modelled to resemble fast and smooth operation of smart transformer. It can vary LV grid voltage with step size of 0.005 p.u. per 0.04 s. The network parameters for the distribution network are presented in Table V in Appendix. This paper focuses on the characterization of network under passive loads only and therefore each bus within the network comprises of an aggregated load.

### B. Load Model

The loads within the distribution network are modeled as dynamic loads. As the objective of this paper is to characterize the network in terms of its active and reactive power response to change in voltage, the sensitivity of the active and reactive power can be represented as [26]:

$$P_{Lk} = P_{Lo}(\frac{V_k}{V_o})^{k_{pv}}(\frac{f_k}{f_o})^{k_{pf}} \tag{1}$$

$$Q_{Lk} = Q_{Lo}(\frac{V_k}{V_o})^{k_{qv}}(\frac{f_k}{f_o})^{k_{qf}} \tag{2}$$

Eqn (1) and (2) represent the variation of active and reactive power as functions voltage and frequency, where $P_{L0}$ and $Q_{Lo}$ are the rated active and reactive power corresponding to nominal voltage, $V_o$ and nominal frequency $f_o$ respectively. $V_k$ and $f_k$ are voltage and frequency at time instant $k$, $k_{pv}$ and $k_{qv}$ are real reactive power voltage exponents, $k_{pf}$ and $k_{qf}$ are real and reactive power frequency exponents. The sensitivity of the load power consumption to frequency has been incorporated as the primary ancillary service provision of interest is frequency response. The load demand at each bus is considered to be time-invariant, with values for each identified in Table VI in Appendix.

Exponents values for different types of loads are given in Table I.

TABLE I: Load Types and Exponent Values [27], [28]

| Load Type | $k_{pv}$ | $k_{qv}$ |
|---|---|---|
| Residential | 1.55 | 4.91 |
| Industrial | 0.5 | 2.4 |
| Commercial | 0.84 | 9.4 |
| Combination | 0.78 | 3.29 |

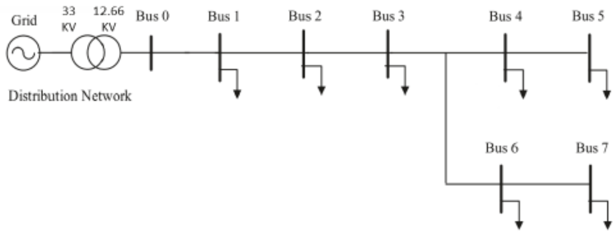

Fig. 1: 7-bus distribution network

## IV. Simulation Results

### A. Methodology

Cases 1 to 4 investigate change in power while decreasing voltage from 1 p.u. until voltage reaches statutory limit of 0.95 p.u., in any point in the network to investigate possible power provision under normal conditions. In cases 5 to 8, voltage is decreased by 0.05p.u. without considering voltage limits to discover sole impact of line resistance. Cases 9 to 12 investigate maximum increase in power consumption following increase in voltage from normal operating conditions until voltage reaches upper statutory limit of 1.05 p.u. in any point in the network. Improved frequency containment of transmission system, delivered by adapting the voltage of multiple LV network is demonstrated in section IV-E.

### B. Cases 1-4. Possible reduction in power consumption - normal conditions

A change in total power consumed by the loads is measured when voltage was decreased from normal operating conditions of 1p.u. at bus 1 until one of the buses reached lower voltage limit of 0.95p.u. In table II, for every case, residential, industrial, commercial and mixed type of load were considered. A change in power is measured as a percentage of total loads power consumption when voltage and frequency are at nominal values at all buses.

$$\Delta P = \left| \frac{P_{nominal} - P_k}{P_{nominal}} \right| \cdot 100\% \tag{3}$$

Eqn (3) represents the variation in power, where $P_{nominal}$ is power consumption when voltages are at nominal values, 1 p.u., at all buses, $P_k$ is current power consumption and $\Delta P$ is change in power. Figure 2 presents methodology using case study 1. The first power consumption measurement is taken when smart transformer is operating under normal condition and voltage is 1p.u. at bus 1. It is indicated with green line in two plots in figure 2. Power consumption is measured for the second time when voltage at one of the buses falls to 0.95p.u. – lowest acceptable value. Change in power demand can be calculated by subtracting the measurements. In all case studies for every load, voltage at bus 7 reached that value first, which is indicated with red line in top and bottom plot in figure 2. For all types of loads, the largest changes in power were observed for the lowest line resistance. In case 4, comparable measurements could not have been taken because of large voltage drop across the network.

TABLE II: Change in load power consumption following voltage change from 1p.u. at bus 1 to 0.95 at bus 7.

| Case No | Load Type | | | |
|---|---|---|---|---|
| | Residential | Industrial | Commercial | Combination |
| Case 1 ($R = R_0$) | 4.81% | 1.65% | 2.60% | 2.52% |
| Case 2 ($R = 0.5R_0$) | 5.16% | 1.76% | 2.79% | 2.71% |
| Case 3 ($R = 5R_0$) | 2.05% | 0.72% | 1.13% | 1.10% |
| Case 4 ($R = 10R_0$) | - | - | - | - |

As shown in table II, voltage at bus 7 was below statutory range when voltage at bus 1 was 1p.u. Voltage change in residential loads resulted in largest values in of power change in case 1, 2 and 3. Lowest values can be observed on industrial loads.

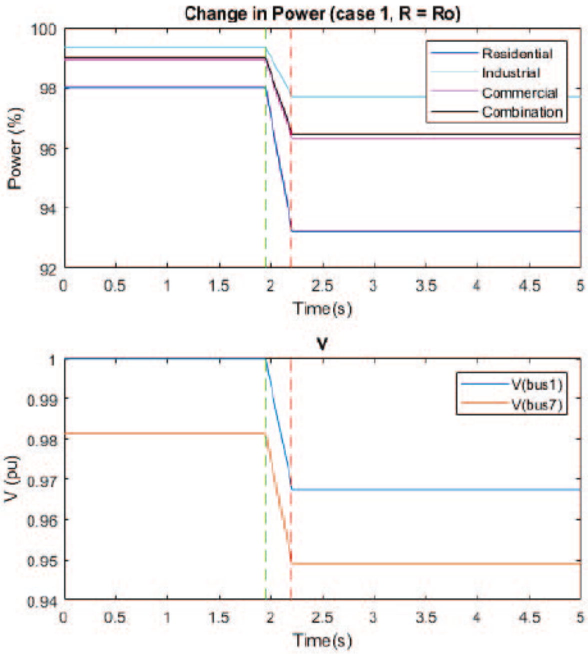

Fig. 2: Change in load power consumption following voltage change from 1p.u. at bus 1 to 0.95 at bus 7

### C. Cases 5-8. Impact of line resistance on reduction in power consumption

Cases 5 to 8 presented in table III do not consider voltage limitations. Change in load power consumption is measured following a decrease of voltage at bus 1 from 1p.u. to 0.95p.u. In this scenario, change is power is dependent mainly on type of load. For the same type of loads, type of network has a negligible influence on change in power. Voltage drop across long lines of network is the limiting factor for power provision through voltage change for networks in case 3 and 4. Networks where voltage drop is more uniform across the network can

TABLE III: Change in load power consumption following voltage change from 1p.u. to 0.95p.u. at bus 1 without consideration for voltage limits.

| Case No | Load Type | | | |
|---|---|---|---|---|
| | Residential | Industrial | Commercial | Combination |
| Case 5 ($R = R_0$) | 7.41% | 2.57% | 4.05% | 3.92% |
| Case 6 ($R = 0.5R_0$) | 7.43% | 2.27% | 4.04% | 3.93% |
| Case 7 ($R = 5R_0$) | 7.3% | 2.63% | 4.11% | 3.97% |
| Case 8 ($R = 10R_0$) | 7.18% | 2.71% | 4.19% | 4.03% |

be more suitable for providing flexibility despite high line resistance.

### D. Cases 9-12. Possible increase in power consumption - normal conditions

Cases 9 to 12 presented in Table IV demonstrate a maximum power consumption increase that the network can offer. Figure 3 presents the methodology using case 9. The first power consumption measurement is taken when smart transformer is operating under normal condition and voltage is 1p.u. at bus 1. It is indicated with red line in two plots in figure 3. Power consumption is measured for the second time when voltage at one of the buses rises to 1.05p.u. – highest acceptable value. Networks with residential loads are most suitable for increasing power consumption. Line resistance has a minimal effect on network's ability to increase power consumption.

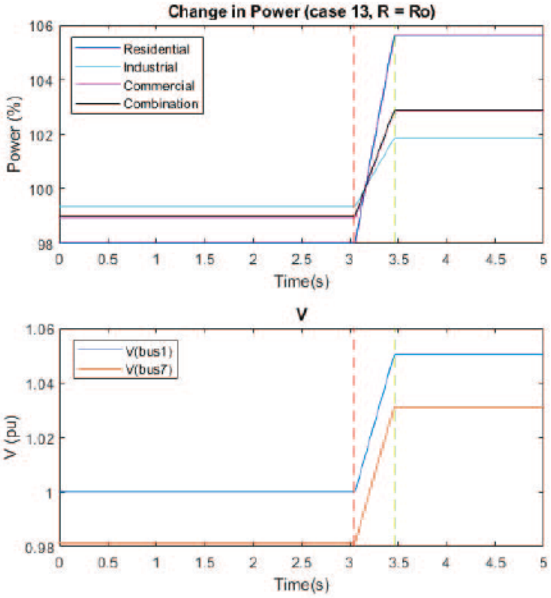

Fig. 3: Change in load power consumption following voltage change from 1p.u. at bus 1 to 1.05 at bus 1

TABLE IV: Change in load power consumption following voltage change from 1p.u. at bus 1 to 1.05p.u. at bus 1.

| Case No | Load Type | | | |
|---|---|---|---|---|
| | Residential | Industrial | Commercial | Combination |
| Case 9 ($R = R_0$) | 7.59% | 2.52% | 3.94% | 3.90% |
| Case 10 ($R = 0.5R_0$) | 7.60% | 2.52% | 3.92% | 3.88% |
| Case 11 ($R = 5R_0$) | 7.50% | 2.56% | 4.01% | 3.93% |
| Case 12 ($R = 10R_0$) | 6.07% | 2.15% | 3.35% | 3.26% |

### E. Application in grid frequency response

This section demonstrates a frequency response of the transmission system enhanced by proposed approach implemented in multiple LV network. A generic system frequency response model , tuned to reproduce Great Britain transmission network dynamics [29], is employed. A frequency event is caused by 500MW power imbalance. When frequency reached lower operational limit, i.e., 49.8 Hz, voltage in distribution network is decreased from normal conditions until one of the buses reaches 0.95 p.u. (as in cases 1-4). Reduction in active power consumption of the network is then scaled by the factor *n*, to demonstrate response of *n* networks. Figure 4 illustrates frequency response with frequency support from none, 1000 and 2000 small residential distribution networks.

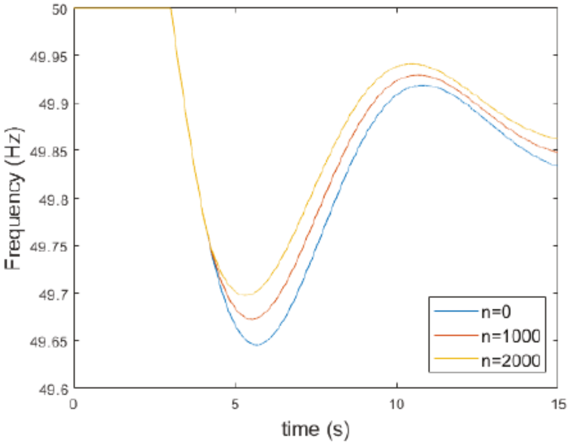

Fig. 4: Frequency response of the transmission network

## V. CONCLUSIONS

In this paper effectiveness of different types of distribution networks in provision of ancillary services to transmission system was evaluated. Frequency support is delivered by adapting the Low Voltage (LV) grid voltage to shape power consumption of voltage-dependant loads in LV network and achieve desired power variation to support frequency containment in the transmission system.

Residential loads and low resistance networks have the biggest potential for decreasing distribution network demand when frequency support is required at transmission network. Voltage drop across long lines of network is the limiting factor for power provision through voltage change. Networks where voltage drop is more uniform across the network can be more suitable for providing ancillary services despite high line resistance. However, when power consumption needs to be increased quickly, line resistance has negligible effect. Change in power depends on type of the load and residential loads can increase power consumption the most while maintaining voltage within limits. Industrial loads are the least effective in decreasing or increasing power consumption of the network. The areas of future work have been identified:

(i) incorporating active devices in the distribution network

(ii) demonstrating frequency support for transmission grid through coordinated change in voltage across multiple distribution networks.

## APPENDIX

TABLE V: Distribution Network Parameters

| Bus ID From | Bus ID To | Resistance (Ω) | Inductive Reactance (Ω) |
|---|---|---|---|
| Bus 0 | Bus 1 | 0.16 | 1.23 |
| Bus 1 | Bus 2 | 0.16 | 1.23 |
| Bus 2 | Bus 3 | 0.47 | 2.23 |
| Bus 3 | Bus 4 | 0.24 | 1.33 |
| Bus 4 | Bus 5 | 0.56 | 2.45 |
| Bus 3 | Bus 6 | 0.24 | 1.04 |
| Bus 6 | Bus 7 | 0.17 | 1.46 |

TABLE VI: Distribution Network Load Demand

| Bus ID | Load Demand (kVA) |
|---|---|
| Bus 1 | 700+100j |
| Bus 2 | 850+250j |
| Bus 3 | 600+150j |
| Bus 4 | 1250+500j |
| Bus 5 | 900+300j |
| Bus 6 | 100+100j |
| Bus 7 | 1000+350j |

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