A Methodology to Study the Impact of an Increasingly Nonconventional Load Mix on Primary Frequency Control

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Abstract—**The last three decades have experienced an impressive growth in loads interfacing with the grid through power electronic devices. These include personal computers and most office equipment as well as industrial induction motors driven by variable frequency drives. The increasing importance of these nonconventional loads has an impact which is yet to be quantified and modeled systematically. This is particularly the case with the natural load-side frequency response, and this lack of knowledge compounds with the current uncertainty in the characterization of the load's natural behavior under frequency disturbances. This paper provides a research roadmap to address this question in a rigorous manner. We propose a bottom-up modeling approach which should provide a deeper understanding of this impact and inform on the way power systems operate under a highly nonconventional load mix during transient frequency events.**

Index Terms—**Load-frequency sensitivity, load modeling, nonconventional load, power electronics, primary frequency control.**

I. INTRODUCTION

FREQUENCY deviations have been, and continue to be, an on going source of concern in the operation of interconnected power systems. In any electric power system, the active power has to be generated almost at the same time as it is consumed to keep the frequency close to its desired value.

At the outset of all generation-demand imbalances, the kinetic energy stored in the rotating generation equipment is rapidly used up (or increased) causing a drop (rise) in the system frequency triggering generator governor response as part of the primary frequency regulation interval [1]. Secondary and tertiary regulation intervals follow on deploying the available reserves allowing the generators providing governor response to return to their original operating set points [2].

Because of their lesser inertia, isolated island power systems, such as that of Great Britain, require adequate provision of energy at all times and in spite of most adverse events to maintain safe operation of their network. Large disturbances, if not quickly corrected, can lead to frequency deviations leading either to under-frequency load shedding, over-frequency generation rejection and ultimately system separation and large-scale blackouts.[1]

To account for any credible frequency excursion, a power system must have a sufficient quantity of spinning generation capacity capable of adjusting its output according to the magnitude of the probable frequency deviations. This spare capacity, which should be distributed across the grid, is generally coined using the generic expression "spinning reserve" which may have variable meanings across national power systems and even within countries [1]. The response provided by spinning reserve occurs in two phases. The primary response acts within tens of seconds of a disturbance to halt the decline (or rise) in frequency; the secondary response then acts to restore the frequency to near nominal within tens of minutes while tertiary control restores secure-economic operation [2].

During frequency excursions not only generators respond to the evolving frequency. Most electric loads are sensitive to changes in the frequency and alter their power consumption as a result. This natural tendency of load to change with frequency increases the damping of frequency dynamics as, generally, the global demand reduces (increases) when the frequency drops (rises). Quantifying the frequency sensitivity of load is a complex empirical parameter identification problem. In spite of this complexity, it represents an important step in the design of effective primary frequency regulation standards and associated control schemes. In Great Britain, for example, it has been found empirically in 1958 that total active power demand decreases approximately by 2% for a fall of 1 Hz in the frequency [3]. This is assumed constant and is still in use today within the operations planning practices of the National Grid. This practice neglects, however, how the loading mix is intrinsically dynamic over the time scales ranging from hours to years.

In this paper, we argue in favor of treating the load-frequency sensitivity as a dynamic factor in the planning of primary frequency regulation means and policies. This is ultimately for improving the technical effectiveness and the economics of this vital function of power system operation. This approach, however, does not lend itself well to direct

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This work was supported by the Engineering and Physical Sciences Research Council through the Supergen FlexNet project, EP/E04011X/1.

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[1] We are reminded that frequency-related events are not confined only to small island power system, however. The November 4th 2006 pan-European Blackout is such an example.

978-1-4244-4241-6/09/$25.00 ©2009 IEEE

empirical approaches relying simply on the record of past frequency deviations. We propose, as an alternative, a research program for the development of a load-frequency sensitivity modeling methodology. The proposal is a bottom-up methodology that relies instead on the estimation of the global system load-frequency sensitivity from appliance population and usage statistics.

Moreover, we argue that this methodology is more appropriate to assess the potential impacts of the growing importance of what we shall call *nonconventional* loads as part of the global demand for electricity. Such loads include appliances with a wide spectrum of ratings (from MW down to almost mW) connected to the grid through the means of power electronic interfaces—variable frequency drives, battery chargers and power supplies. The load-frequency sensitivity of these appliances is eminently different from their *conventional* counterparts. Some of the mainstream hypotheses indicate that nonconventional loads are quite insensitive to frequency deviations and that consequently their increasing presence in power systems will require a reassessment of primary frequency regulation practices. This methodology is also well suited to formulate scenarios for the global evolution of the load-frequency sensitivity taking the changing load mix into account. Ultimately, the methodology could help in informing operators on the potential impacts of a "stiffer" load on power system operation and planning. Moreover, it could help propose modifications to appliance designs and industrial practices to make nonconventional loads more flexible.

II. BASIC LOAD CLASSIFICATION

Currently, electric demand from all sectors (residential, commercial, industrial) form a mix of what we shall call *conventional* and *nonconventional* loads. We argue that the two classes of loads have differing responsiveness against frequency upsets.

On one hand, conventional loads are appliances whose bulk power consumption happens over combinations of (equivalent) resistances, inductances and capacitances (RLC); these include induction motors, resistive heaters, incandescent lamps, conventional ovens, etc.

It is straightforward to estimate the load-frequency sensitivity of individual conventional loads from analytical studies of their equivalent circuits [4]. For example, the built-in frequency dependence in induction machines' power consumption is caused by the fact that machines slow down when the frequency drops, which incidentally leads to lessened power demand.

On the other hand, in nonconventional loads the bulk power consumption happens within circuitry containing power electronic switching elements (diodes, transistors and thyristors) in combination with (equivalent) RLC elements. These include, for example, fluorescent lamps, motors connected through variable speed drives, battery chargers, computers, and a wide spectrum of electronic home and office appliances. Unlike in the case of conventional loads, it is not so straightforward to evaluate the load-frequency behavior of these appliances because of the complex switching patterns intermittently connecting different equivalent RLC elements with the grid. Therefore, new approaches must be developed in assessing those loads' frequency sensitivities.

III. NATURAL LOAD-FREQUENCY SENSITIVITY

The load-frequency sensitivity contributes non-negligibly to the primary frequency response requirement of most power systems. For example, in the British system, a generation loss of 1050 MW in Scotland on 19th April, 2007 caused a maximum frequency drop of 0.303 Hz. The total system demand prior to the loss was 45,275 MW. At the time when the minimum frequency was reached, the total change in output from generators providing spinning reserves was 500 MW. Frequency-responsive reserve in Scotland increased by 100 MW while 80 MW of demand-side reserve was tripped when the frequency attained 49.7 Hz. Overall nationally, 680 MW of the total response was supplied through frequency responsive ancillary services. Yet, it is the frequency sensitivity of the load which supplied the difference: 1050 – 680 = 370 MW. In other words, 36% of the post-fault response was accounted for by the natural load-frequency sensitivity only [5]. This example shows how important the natural negative feedback the frequency can have on the demand in such critical times.

The swing equation ties the load-frequency sensitivity to the rest of a grid's power-frequency dynamics [6], [7]

$$H\frac{d\Delta\omega}{dt} = P_M - P_E - D\Delta\omega \tag{1}$$

In (1) the time rate of change of the system angular frequency deviations $\Delta\omega = 2\pi\Delta f$ is driven primarily by the imbalance between the mechanical power input from the system generators P_M and the system electrical load P_E. In addition, the natural response to frequency deviations $D\Delta\omega$ contributes to reduce the load generation imbalance during power-frequency transients. The constants H and D are respectively the system's inertial and load-frequency sensitivity constants.

The values of H and D are fundamental in describing the power-frequency dynamics of a given power system. A large inertia entails slow frequency dynamics in response to generation-load imbalances. Likewise, a positive-valued load-frequency sensitivity entails that the load naturally provides negative feedback in compensating generation-load imbalances. This negative feedback helps in reducing the amount of generation primary governor response in steady state *and* introduces some damping by slowing down the rate of change of the frequency deviations.

It is therefore clear that there is interest in having a better idea of what value D is taking. Having better information about its value is critical in designing improved primary frequency control strategies. To this end, the focus of this paper is on the determination of D and its future evolution. Past published work on this topic is very scarce. The determination of this value is usually either based on estimations [8] or generally lacks robust supporting evidence [9], [10].

A. *Load-Frequency Characteristics*

A comprehensive review of the existing literature indicates that the majority of research into the load-frequency response focuses either on single composite loads [10], on examining a number of larger-generator in-feed losses [5] or parts of whole systems [12]–[15]. The load frequency sensitivity is quoted generally in percent power reduction per hertz drop.

For example, if we consider motoring loads, these represent a very wide proportion of typical total system loading, accounting for 40 to 60% [16]. Moreover, magnitude of the global system motoring load is sensitive to voltage and frequency changes. It can be found that per-unitized changes in frequency have a larger impact on motor load changes than voltage deviations. Typically, a 1% decrease in the frequency leads to approximately a 2% decrease in the motoring load magnitude [4].

As mentioned previously, National Grid, the transmission system operator in Great Britain, currently uses a constant value of 2% MW/Hz. This value was derived through earlier investigations [3]. Further investigations indicated that load-frequency sensitivity could be refined to a value closer to 2.5% MW/Hz [17].

In addition, the IEEE Task Force on Load Representation published figures in 1993 describing load-frequency sensitivities based on the following load subdivisions [10]:

- Residential loads: 1.4 – 2.0% MW/Hz
- Commercial loads: 2.0 – 2.8% MW/Hz
- Industrial loads: 2.2% MW/Hz
- Aluminium refineries: –0.5% MW/Hz
- Steel mills: 2.5% MW/Hz
- Power auxiliary plant: 4.8% MW/Hz
- Agricultural pumps: 9.3% MW/Hz

Kundur in his classic text [7] provides further measured values of voltage/frequency dependent characteristics of real and reactive power for a number of important loads (see Table I). The values of D in Table I are found in the column corresponding to the values of $\partial P/\partial f$.

By inspection of Table I, we find that the vast majority of applications would provide the beneficial negative feedback (through $D = \partial P/\partial f > 0$) needed to help limiting the magnitude and the rate of change of frequency deviations.

The information in Table I and above is generally insufficient, however, to give a good estimate of a power system's load-frequency sensitivity. This is so because demand for electricity is dynamic over time in magnitude and in nature, that is $D = D(t)$. Hence, an appropriate model of the load-frequency sensitivity has to go beyond the assessment of individual load's sensitivity; it has to attempt to model properly the load usage and its population patterns.

B. *Other Factors of Influence on Frequency Dynamics*

Whereas load-frequency sensitivity is fundamental in frequency dynamics, the characteristics of the generation system [as seen in (1)] and its frequency regulation controls also play a very significant role [7]. These characteristics include:

- Speed governor droop settings;
- Magnitude of power deficit / surplus;
- System inertia; and,
- Proportion of the response provided by specific generating units.

These characteristics form the basis of classical primary frequency control schemes. Nevertheless, the full description of these is outside the scope of this paper (as we shall focus on the natural contribution of the demand to this function only here). We point the interested readers to the extensive literature on these topics; see, for example, the classic texts by Wood and Wollenberg [6] and Kundur [7].

TABLE I

MEASURED VALUES OF VOLTAGE/FREQUENCY REAL/REACTIVE POWER SENSITIVITIES OF TYPICAL LOADS (IN P.U) [7]

	Sensitivities				
Load type	$\partial P/\partial V$	$\partial Q/\partial V$	$\partial P/\partial f$	$\partial Q/\partial f$	Power Factor
Air Conditioning					
3-phase central	0.088	2.5	0.98	−1.3	0.90
1-phase central	0.202	2.3	0.90	−2.7	0.96
Water heater, range top, oven, deep fryer	2.0	0	0	0	1.0
Dishwasher	1.8	3.6	0	−1.4	0.99
Clothes washer	0.08	1.6	3.0	1.8	0.65
Clothes dryer	2.0	3.2	0	−2.5	0.99
Refrigerator	0.77	2.5	0.53	−1.5	0.8
Television	2.0	5.1	0	−4.5	0.8
Incandescent lights	1.55	0	0	0	1.0
Fluorescent lights	0.96	7.4	1.0	−2.8	0.9
Industrial motors	0.07	0.5	2.5	1.2	0.88
Fan motors	0.08	1.6	2.9	1.7	0.87
Agricultural pumps	1.4	1.4	5.0	4.0	0.85
Arc furnace	2.3	1.6	−1.0	−1.0	0.70
Transformer (unloaded)	3.4	11.5	0	−11.8	0.64

IV. NONCONVENTIONAL LOADS AND FREQUENCY RESPONSE

The change in the variety within the load mix is placing new strains on the electrical network. The greatest change in the load mix has been the fast growth of loads with power electronic interfaces, *i.e.* nonconventional loads. The most important categories of nonconventional loads include power supplies and battery chargers (for ac to dc power conversion) and variable speed drives (for ac to ac power conversion).

In the last decades, internal/external power supplies and battery chargers have become increasingly important to the operation of many electrical and electronic products. They accompany portable and static appliances which are found in growing numbers in household and office environments. These products are estimated to consume an important portion of daily electricity production. For example, within the United States, it has been estimated that there are currently about five external power supplies per person and that the total electricity flowing through those types of power supplies has been estimated at 6 percent of the U.S. national electric bill (300 billion kWh per year) [18].

Moreover, with oncoming stricter regulation on CO_2 emissions, there is an expected dramatic increase in the funding for the electrification of transport and especially for the development of the infrastructure to recharge plug-in hybrid and electric cars. This dramatic change in the foreseeable loading mix will introduce an increased use of electricity by land transportation from which the energy will ultimately transit through power electronic interfaces.

Variable-speed drives are also being increasingly adopted as standard within industrial motion and process control applications. Their variable speed gives greater operational flexibility at a lower initial and operating cost when compared to some variable-speed motoring applications based on dc motors and drives. With its added flexibility and savings potential, the EU-funded SAVE II Programme has identified large-scale application of variable speed drives as the motor systems technology having the most significant energy savings potential. Energy savings brought about by electrical drive system alone are projected to be 6 billion kWh per annum in the U.K. [19].

The current and foreseen rapid expansions in nonconventional loads in proportion to the total system load are reshaping the way the load responds to changes in the frequency. The hypothesis is that, unlike conventional loads, nonconventional loads have no or limited correlation between the system frequency and their power consumption [20]. Thus, it is logical to assume that *D* will be slowly decreasing as this penetration increases. The next section outlines the research agenda we have set to assess this potential drop and other changes in load response and their impacts on future power system operation.

V. PROPOSED MODELING METHODOLOGY

The evolving nature of the load mix in most power systems and the lack of understanding of its impact on the load-frequency sensitivity bring into focus the importance of an accurate understanding of the contribution of *D* in frequency dynamics. The course of research we propose here is exactly that. We are on course to develop a comprehensive methodology to model demand and its frequency sensitivity in the context of a growing nonconventional loading mix.

Load modeling is a complex task that is compounded by a number of great uncertainties: 1) the large quantity and variety of individual load components, 2) the physical location of the loads, 3) the change of load behavior and sensitivity according to time of day, season and weather, and 4) the lack of accurate load component characterization alongside its corresponding data.

A. Quantifying D

In order to obtain a better understanding of *D* and address the uncertainties with load modeling, we propose a bottom-up approach. We first examine the load mix through its classification into a number of categories. Fig. 1 illustrates this approach: For each load category an appliance model and a usage model are to be built or extracted for the literature. The appliance model will identify the load-frequency sensitivity of a generic single appliance, whereas the usage model will specify patterns of use as well as the appliance population. Both sub-models will contribute to quantifying *D* for every category. The value of *D* per category is to be aggregated into a nationwide or regional value as required. The key point here is that this model will be able to map dynamically the power-frequency behavior of demand from a finite set of parameters.

The research challenge resides in the identification of the parameters with the most influence as well as recognizing the load categories with the highest potential positive or negative impacts. Moreover, there is a need to quantify the uncertainty about the value of *D* reflecting the indeterminate nature of the load mix, of its characteristics and underlying data. A number of standard statistical methods (e.g. hypothesis testing and regression analysis) and Monte Carlo simulation will be used to address those issues.

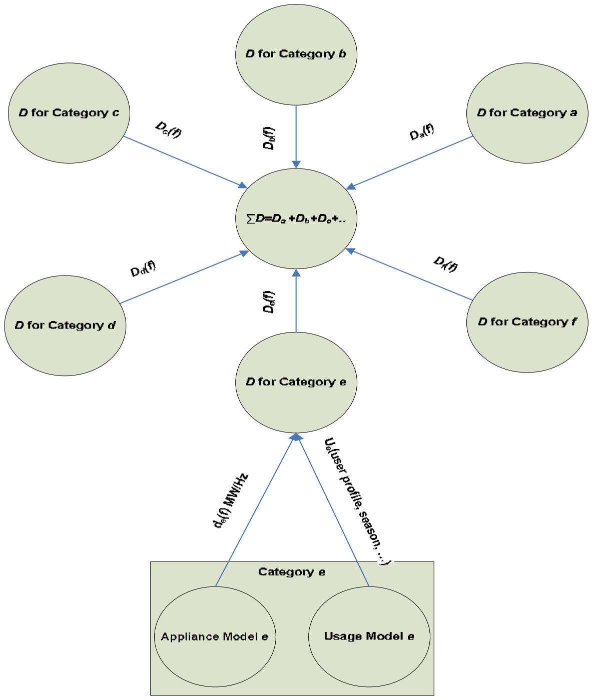

Fig. 1 Schematic representation of the methodology for quantifying the load-frequency sensitivity

1) Classification of Loads

The identification of the load mix consists first of breaking down the loads into meaningful categories. The U.K. government Market Transformation Programme, as part of the European Union Energy Using Products (EuP) Directive, has provided many preparatory studies on product categories, breaking down their energy consumption (into electrical and others). For the purpose of this work, we will retain 17 of those product categories [21]. These include:

1. Boilers and combi-boilers (gas/oil/electric)
2. Water heaters (gas/oil/electric)

3. Personal computers (desktops and laptops) and computer monitors
4. Imaging equipment: copiers, faxes, printers, scanners, multifunctional devices
5. Consumer electronics: televisions
6. Battery chargers and external power supplies
7. Office lighting
8. (Public) street lighting
9. Residential room conditioning appliances (air conditioning and ventilation)
10. Electric motors 1-150 kW, water pumps (commercial buildings, drinking water, food, agriculture), circulators in buildings, ventilation fans (non-residential)
11. Commercial refrigerators and freezers, including chillers, display cabinets and vending machines
12. Domestic refrigerators and freezers
13. Domestic dishwashers and washing machines
14. Simple converter boxes for digital television
15. Domestic lighting
16. Laundry dryers
17. Vacuum cleaners

This list may need to be extended when considering future scenarios or it may well be too exhaustive, especially given the very intermittent use of some of the appliances listed (*e.g.* vacuum cleaners).

2) *Appliance Model*

Previously we have mentioned some of the load-frequency sensitivities for various load categories (essentially conventional). However, for categories where the literature does not examine or provide the load-frequency sensitivity, an evaluation of their load-frequency characteristics will be conducted using standard circuit simulation software. This is especially the case for nonconventional loads (*e.g.* battery chargers, computing equipment and variable frequency drives). We acknowledge that there is a vast diversity in the number of power electronic interface designs for these appliances. However, for most types of interfaces the fundamental circuit design principles are the same with only slight differences across models and manufacturers. Therefore, we will study the most popular designs and then adopt a generic circuit for each type of appliance. This will obviously introduce some level of error; however, this should not influence greatly the main results of the research which entails getting a generic model of a large population of a wide array of different appliances.

3) *Usage Model*

To build an accurate usage model per category, a number of drivers are being thoroughly investigated. These include:

- Appliance population (current and forecasted)
- Usage pattern (season, time of day, etc.)
- Power consumption
- User profile
- Type of use (on, off, standby)
- Load profile
- Load factor

Obviously, some factors will have more impact than others for each type of appliance. Regression analyses based on available usage statistics are currently being developed and used in determining those impacts.

4) *Generation*

We note, however, that in this context studying the load in isolation is not sufficient. The characterization of the load-frequency sensitivity is tied to the generation system's frequency response as illustrated by the swing equation (1).

Generation and wider power system models will be integrated to consider a number of variables and drivers such as the system inertia, the potential magnitude of the generation-load imbalances, generator governor settings, etc.

B. *Sensitivity Analysis*

The modeling methodology will be providing a very high level of complexity and sophistication. This calls for an extensive program of sensitivity analysis for discovering which are the key drivers affecting the load-frequency sensitivity of demand and to assess the robustness of the derived models. The building of scenarios for the evolution of the loading mix will also be part of this exercise. This scenario analysis should also be useful to direct the development of the technologies best suited to improve the load-frequency sensitivity in cases where the loading mix may become such that it provides very little help in stabilizing the frequency.

C. *Calibration and Validation*

We will calibrate and validate the model against recently recorded system disturbances. The challenge here will reside in determining which of the many possible parameters of the model should be modified to best fit the observed behavior. For this purpose, involvement of transmission system operators is expected.

VI. EXPECTED OUTCOMES

The research will yield a systematic methodology capable of determining the dynamic value of D. The methodology will help articulate a number of important findings:

1. The load-frequency sensitivity is a dynamic value. Accounting for the load-frequency sensitivity as a static constant sometimes creates situations where, given the actual value of D, the system generation-side primary reserves may be overly high causing excessive preventive security costs. On the other hand, an opposite situation in which the estimate for D is much higher than its true value is equally (if not more) inadequate because it may lead to a lowered first line of defense against fast-evolving generation-load imbalances.
2. The increased penetration of nonconventional loads will likely decrease the value of the load frequency sensitivity thus placing a strain on generation-side primary reserve response. Therefore, the methodology proposed in this work should be the first step in the redesign of primary frequency control strategies and generation-side primary reserve scheduling.
3. The methodology will identify the key drivers behind frequency sensitivity, thus becoming a policy evaluation

mechanism to facilitate in improving the system primary frequency regulation and product manufacturing, leading to the incorporation of frequency sensitivity technology in power electronic devices.

4. The methodology will provide a platform to help predict the future trend of D as the load and generation mix evolve. With emission regulations placing a greater constraint on the type of generation (for instance, within the U.K. there is a high probability that the generation mix could be dominated by rather inflexible and non-responsive nuclear and wind generation) there will be a greater demand to transfer some of the burden of frequency regulation functions from generation to load.

These expected results could be translated into multiple tangible advantages for power electric systems. As a concrete example of such potential benefits, a study conducted on the Taiwan Power Company network about incorporating a more dynamic value for its load-frequency sensitivity into the real-time dispatch resulted in the reduction in the cost of dispatch by 21.87% [22]. Moreover, as there are proposals for markets for frequency regulation services [2], [23], one could foresee groups of consumers aggregating their load-frequency adjustment potential and offer it into such a market in direct competition with generators. The pre-condition for this happening is exactly what this methodology will be providing: a way for consumers to characterize their load-frequency response so that they can formulate proper market offers.

VII. CONCLUSION

This paper presented the research roadmap to a systematic bottom-up methodology to understand a power system's load-frequency sensitivity and its impact on primary frequency regulation. This is even more important given the evolving nature of the load mix which is more and more characterized by the presence of power electronic interfaces. This research will bring into focus the importance of a more accurate understanding of the contribution of this in the behavior of frequency in power systems. Furthermore, it will identify the key drivers affecting the frequency sensitivity of demand and provide a clearer guidance for policy pertaining to control schemes for primary frequency regulation and product manufacturing.

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