Combining Flexible Loads with Energy Storage Systems to provide Frequency Control

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***Abstract*—This paper proposes a method of using flexible loads which switch on and off to provide frequency control based on a probability function. The proposed control strategy combines flexible loads with an energy storage system (ESS) in such a way that the flexible loads are responsible for providing support to larger power imbalances whereas the ESS compensates smaller ones. Simulation results based on the well-known WSCC 9-bus system indicate that the controller improves the overall frequency response of the system while maintaining acceptable voltage profiles, and allows for better use of the capacity of the ESS.**

***Index Terms*—Demand side management, flexible loads, energy storage systems, response fatigue, discrete control.**

I. Introduction

A. Motivation

Demand Side Management (DSM) is considered an essential component in the successful evolution of the power system. As a matter of fact, DSM is already being used by Transmission System Operators (TSOs) to manage critical situations of the grid. For example, the TSOs of France and Italy used 1.7 GW of interruptible load as a response to the European network split on 8 January 2021 [1]. The motivation for this work came about based on experience gained by the first author whilst working with an Irish DSM unit that performs ancillary services on behalf of the TSO.

Converter-interfaced Energy Storage Systems (ESSs) are another emerging key component of modern power systems [2]. ESSs have gained high interest in recent years due to their ability to add increased flexibility to power systems by facilitating the penetration of non-dispatchable power production mainly in the form of Renewable Energy Sources (RESs). Although ESSs have seen significant advancement in recent years, the ability to use ESS to perform large scale frequency control has not been feasible due to capacity constraints which have made it economically unviable.

This paper proposes a decentralised control of flexible loads combined with an ESS. This control exploits the strengths of these methods, namely the loads are responsible for compensating larger disturbances and the use of the ESS is restricted to smaller disturbances.

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B. Literature review

One of the primary reasons that demand type programs have gained attention is due to the fact that the potential resource is quite large with the infrastructure already in place and not much additional investment is required to allocate loads to these programs. Using flexible loads rather than conventional methods have also several other advantages [3]: (i) large groups of small loads have lower variability than a small group of large power plants; (ii) faster response than conventional power plants; and (iii) even distribution throughout the grid.

Among practical implementations of DSM, cooling and refrigeration units are particularly relevant as they are easily controllable due to their ability to store energy through gradients in temperature and the available resource is huge [4]. For example, in California there is an estimated 4 GW of non-coincident load, i.e., loads that are not used at the same time [5]. It is estimated that 50% of electricity consumption in the USA comes from refrigeration units [6].

Another potential application of DSM is the utilization of Electric Vehicles (EVs). In this context, [7] studies the charging cycles of an electric car using DSM with the aim to achieve financial savings and reduce peak load demand. In the same vein, the work in [8] discusses the idea of using EVs as distributed energy resources to support the power grid during severe system loading and outages.

The combination of DSM with ESSs is studied in [9] and [10]. In this study a simplified model of an ESS is used with many other models existing such as the ones presented in the book [2] and in [11], [12]. The limitations of the ESS that this paper attempts to overcome are discussed in detail in [13]. One of the main challenges which faces load control programmes is trying to achieve end user acceptance. This challenge is thoroughly discussed in detail in [3] and [14]. The works in [15] and [16] analyse the importance of flexible loads for the integration of RESs, which introduces many power system instability problems as indicated in [17] and [18].

C. Contributions

The specific contributions of the paper are as follows:

- A decentralised and clusterised control that determines how clusters of flexible loads switch on/off to perform frequency control based on frequency measurements.
- A coordinated control that combines the clusterised load control above with an ESS.

The proposed control strategies are tested through computer-based simulations and a comprehensive set of scenarios. With this aim, we use the software tool Dome [19] that is able to simulate power systems modelled as a set of Hybrid Differential-Algebraic Equations (HDAEs) [20], [21], and the WSCC-9 bus system [22] for all simulations.

D. Organization

The remainder of the paper is organized as follows. Section II presents the power system model used in the simulations. Section III discusses DSM and the necessary conditions for one such programme to be implemented successfully. Section IV proposes the method of control to determine how the loads switch. Section V gives a brief description of the ESS model used and combines the ESS and the controller. Finally, conclusions and future work are discussed in Section VI.

II. Hybrid power system model

Power systems can be formulated as a set of nonlinear HDAEs [23], as follows:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u},\boldsymbol{z})\,, \\ \mathbf{0}_{n_y,1} &= \boldsymbol{g}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u},\boldsymbol{z})\,, \end{aligned} \tag{1}$$

where $\boldsymbol{f}$ are the differential equations, $\boldsymbol{g}$ are the algebraic equations, $\boldsymbol{x}$, $\boldsymbol{x} \in \mathbb{R}^{n_x}$ are the state variables, e.g. generator rotor speeds, and $\boldsymbol{y}$, $\boldsymbol{y} \in \mathbb{R}^{n_y}$, are the algebraic variables, e.g. bus voltage angles; $\boldsymbol{u}$, $\boldsymbol{u} \in \mathbb{R}^{n_u}$, are the inputs, e.g. load forecast; and $\boldsymbol{z}$, $\boldsymbol{z} \in \mathbb{N}^{n_z}$, are the discrete variables, e.g. status of the machines.

The set of nonlinear HDAEs (1) is a special case of a singular system of nonlinear hybrid differential equations in the following form:

$$\mathbf{E}\dot{\boldsymbol{\xi}} = \boldsymbol{F}(\boldsymbol{\xi},\boldsymbol{u},\boldsymbol{z})\,, \tag{2}$$

where

$$\mathbf{E} = \left[\begin{array}{cc} \mathbf{I}_{n_x} & \mathbf{0}_{n_x,n_y} \\ \mathbf{0}_{n_y,n_x} & \mathbf{0}_{n_y,n_y} \end{array} \right], \quad \boldsymbol{\xi} = \left[\begin{array}{c} \boldsymbol{x}(t) \\ \boldsymbol{y}(t) \end{array} \right],$$

and

$$\boldsymbol{F}(\boldsymbol{\xi},\boldsymbol{u},\boldsymbol{z}) = \left[\begin{array}{c} \boldsymbol{f}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u},\boldsymbol{z}) \\ \boldsymbol{g}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{u},\boldsymbol{z}) \end{array} \right].$$

An hybrid system is a set of systems of differential equations where transition conditions from one system to another in that set of systems play an important role. This can be easily seen from the following example. Let $\boldsymbol{z} \in \{\boldsymbol{z}_1, \boldsymbol{z}_2\}$, $\boldsymbol{z}_1, \boldsymbol{z}_2$ constant vectors in $\mathbb{N}^{n_z}$; $\boldsymbol{z}_1, \boldsymbol{z}_2$ can then be considered as two different modes and (2) can be split into two systems:

$$\begin{aligned} &\mathbf{E}\,\dot{\boldsymbol{\xi}} = \boldsymbol{F}(\boldsymbol{\xi},\boldsymbol{u},\boldsymbol{z}_1), \text{ and} \\ &\mathbf{E}\,\dot{\boldsymbol{\xi}} = \boldsymbol{F}(\boldsymbol{\xi},\boldsymbol{u},\boldsymbol{z}_2). \end{aligned}$$

In this case, there will be two systems of singular non-linear differential equations. However, the index set of the mode transitions as well as the transition conditions should be taken into account and defined. In general, (2) can be rewritten as $\mathbf{E}\dot{\boldsymbol{\xi}} = \boldsymbol{F}(\boldsymbol{\xi},\boldsymbol{u},\boldsymbol{z}_i)$, $i = 0,1,2,...,N$, $\boldsymbol{z}_i$ constant. Then each singular nonlinear system is only defined in a certain interval $t \in [t_i, t_{i+1})$, $i = 0,1,2,...,N$.

Equations (1) and (2) are utilised to emulate the transient behavior of power systems. These equations include the dynamic models of synchronous machines and their frequency and voltage controllers (e.g., turbine governors and automatic voltage regulators), the dynamic model of the ESS, and the discrete model of the proposed controller. A description of the discrete decentralised controller of loads and ESS is given below. The interested reader is referred to [23] for a thorough description of all others models.

III. Discrete Decentralized Control of Loads

The controller proposed in this study works by loads switching on and off based on frequency measurements to provide frequency control to the system. The controller is decentralized i.e., each load switches based on a local frequency measurement and is independent from the activity of all other loads within the system. The proposed controller works by having N loads distributed within the system with the initial amount of loads which are connected to the system being N_0. For simplicity, in this work, N_0 is always chosen to be $N/2$. This way no matter if the frequency goes above or below the nominal frequency the controller will be able to switch loads on (above nominal) and shed load (below nominal). Furthermore, a probability q is utilised at every time step (Δt) to decide if a load switches on or off. The value for q is proportional to the frequency deviation (Δf). Mathematically this can be written as follows. Let us define the quantity $\tilde{q}$ as:

$$\tilde{q}(t) = \frac{\Delta f(t) + \Delta f_{\max}}{2\Delta f_{\max}} \tag{3}$$

where $\Delta f_{\max}$ is the maximum allowable frequency change such that beyond this point full load reserve will be used. Then, the probability q is given by (see also Fig. 1):

$$q(t) = \begin{cases} 0 & \text{if } \tilde{q}(t) \leq 0, \\ 1 & \text{if } \tilde{q}(t) \geq 1, \\ \tilde{q}(t) & \text{otherwise.} \end{cases} \tag{4}$$

Once the value of q is determined, each load independently generates a random number, u, between 1 and 0 using a uniform distribution. If $u \leq q$, the load will switch on, and switch off otherwise. In this study $\Delta f_{\max} = 0.2$ Hz and $\Delta f_{\min} = -\Delta f_{\max}$, where the nominal frequency is 60 Hz. Outside the range [59.8, 60.2] Hz, the full amount of reserve is connected for the upper bound and disconnected for the lower bound.

A. Impact of the switching time step

Figure 2 compares the impact on the frequency of the Center of Inertia (CoI) of two different switching time steps, namely $\Delta t = 2.5$ s and $\Delta t = 0.1$ s. Both cases have 50×1 MW loads with N_0 being 25×1 MW. Finally, a 25 MW load outage is considered as a contingency.

The smaller the time step, in this case $\Delta t = 0.1$s, makes the switching of the loads to happen more often and, as shown

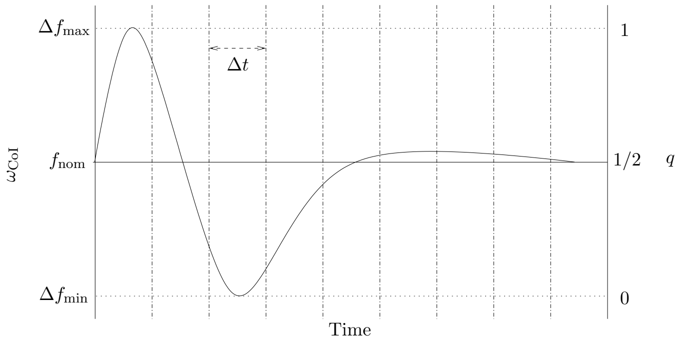

Fig. 1: Visualization of the determination of the probability q.

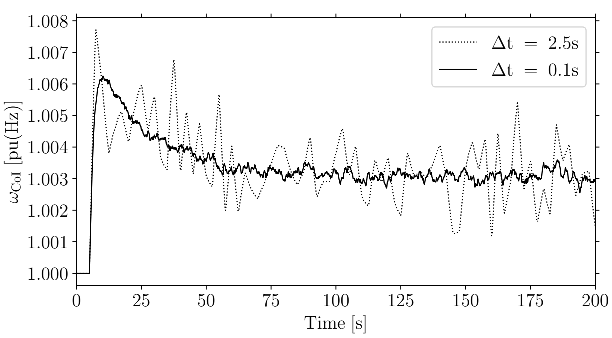

Fig. 2: Controller value comparison.

in Fig. 2, this is beneficial for the overall frequency response of the system. On the other hand, low granularity in terms of either power steps or time steps, distorts more the frequency. The level of granularity appears to be particularly relevant for systems with low inertia where the effect of large "jumps" is magnified [17], [18].

IV. Clusterised Control

The example discussed in the previous section indicates the load-switching controller works the better the smaller the time steps with which the loads are switched. However, in practice, these loads represent sites which have to maintain a certain level of service continuity and quaility for their customers/business. This means that the time step cannot be too small. This issue is discussed in this section.

With load frequency control schemes end user acceptance is an important factor. If a consumer is constantly being called upon to supply a load they may withdraw from the ancillary service programme, possibly when the capacity is most needed. This phenomenon is known as response fatigue. This dual competing objective which exists is one of the main challenges which faces load control programmes. The two objectives being, providing reliable support for the grid while at the same time the supplier providing an adequate level of service.

To overcome this phenomenon, this paper puts each of the loads into cluster/group. The amount of switching events is equal the amount of clusters available meaning that each cluster can only switch once and therefore each load can only switch once. Over the time frame of a fault the amount of switching events is defined as $t_{\mathrm{fault}}/N_{\mathrm{cluster}}$ where N_{cluster} is the amount of available clusters. The time taken for t_{fault} is 50 s as beyond this period the secondary frequency control will begin to act. A comparison is carried out between the original controller which works like a discrete ESS as the time step becomes sufficiently small and the clusterised controller. A 50 MW load outage is simulated with parameter controllers given in Table I.

TABLE I: Parameters of the clusterised controllers.

Original Controller	Clusterised Controller
$N = 200$	$N = 200$
$N_0 = 100$	$N_{\mathrm{size}} = 10$
	$N_{\mathrm{cluster}} = 20$
$\Delta t = 0.05\mathrm{s}$	$\Delta t = \frac{50}{20} = 2.5\mathrm{s}$
$\Delta f_{\max} = 0.2\mathrm{Hz}(0.0033\mathrm{pu})$	$\Delta f_{\max} = 0.2\mathrm{Hz}(0.0033\mathrm{pu})$

The comparison of the transient response of the frequency for the original and clusterised control is shown in Fig. 3. The original fault is shown for visualisation purposes. As expected, the original controller has a substantially more favourable response with a very low frequency deviation considering the magnitude of the disturbance. The clusterised controller performs quite well for the initial disturbance over the first 50 s. The steady-state fluctuations introduced by the switching events is not favourable from a frequency and consumer satisfaction point of view. Eradicating this is addressed in the next section.

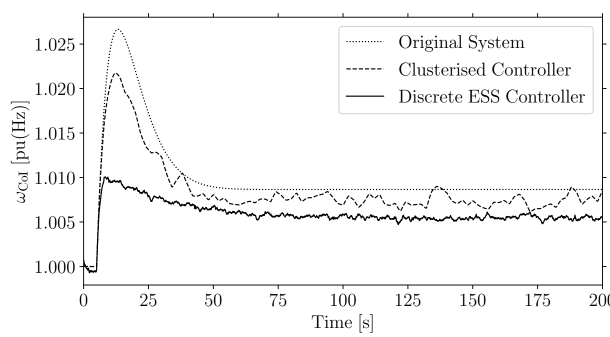

Fig. 3: Comparison on controller methods.

The clusterised controller assumes that the size of the clusters are 20×1 MW loads meaning that every time step 20 possible loads can switch. For larger faults such as this one the controller works well, but if this same cluster size is applied to a much smaller fault within the system it may not work as favourably.

V. Clusterised Control coupled with an ESS

As was pointed out in the previous section, the method of using flexible loads which switch independently can be useful for larger faults within the system, but as the imbalance's in the system were smaller the controller did not work as well as its parameters must stay fixed over a given fault period. In this section, an ESS is used such that within a certain frequency range only the ESS will act and outside this range the controller will act alongside the ESS. This is done by using a frequency dead band [24], [25]. As the capacity of the ESS becomes larger the speed at which it can discharge energy decreases but is less likely to run out of energy while compensating. Lower capacity ESSs can act faster but the likelihood of hitting energy limits whilst discharging is increased. Combining the two methods of control attempts to exploit the respective weakness of each form of control.

The model of the ESS is shown in Fig. 4. The input signal ω_{CoI} is regulated through active power while voltage at the connection point is regulated by reactive power. The two lag blocks $T_{\mathrm{P,ESS}}$ and $T_{\mathrm{Q,ESS}}$ describe the behaviour of the dynamics of the ESS. A PI controller is used to regulate active power while a lead/lag controller is used to regulate reactive power. Previously, the probability value q would be generated

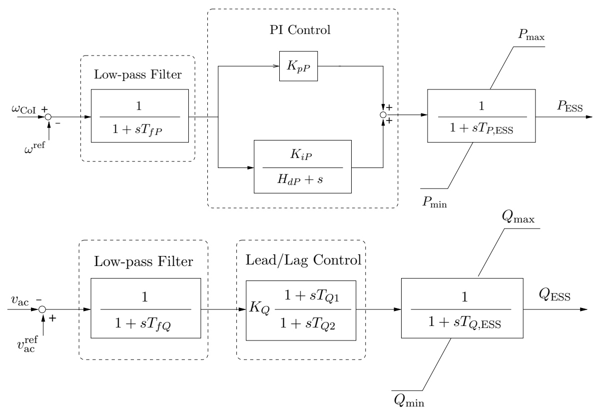

Fig. 4: Control diagram of the ESS model.

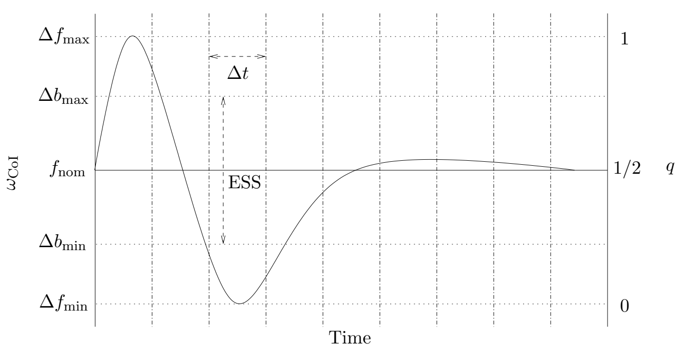

Fig. 5: Visualization of the determination of the probability q with deadband.

for any changes in frequency and loads would switch based on this q value. However, now we assume that q will only be generated outside the dead band frequency range (see Fig. 5 and (5)).

$$q(t) = \begin{cases} 0 & \text{if } \tilde{q}(t) \leq 0, \\ 1 & \text{if } \tilde{q}(t) \geq 1, \\ q(t-\Delta t) & \text{if } \Delta b_{\min} \leq \tilde{q}(t) \leq \Delta b_{\max}, \\ \tilde{q}(t) & \text{otherwise.} \end{cases} \tag{5}$$

where $\Delta b_{\min}$ and $\Delta b_{\max}$ are the minimum and maximum frequency range of the dead band with $\Delta b_{\min} = -\Delta b_{\max}$.

To test the coupled ESS and controller four different load outage sizes are simulated to show the different regions of operation, namely, 10 MW, 20 MW, 40 MW and 60 MW. First, we show the case of just the primary frequency control (see Fig. 6). Next, Fig. 7 shows the case where the controller is included. Last, Fig. 8 shows the case when the Automatic Generation Control (AGC) is included. A substantial reduction has been made to the initial disturbances for all cases when the controller is included (Fig. 7). Each case is described below:

- **10 MW:** The frequency does not cross $\Delta b_{\max}$ or $\Delta b_{\min}$ therefore only the ESS acts.
- **20 MW:** One switching event is only required to get frequency between $\Delta b_{\max}$ and $\Delta b_{\min}$ where ESS takes over
- **40 MW:** A few switching events possibly 5 or 6 until ESS takes over.
- **60 MW:** Many switching events with the steady state settling point being greater than $\Delta b_{\max}$ or $\Delta b_{\min}$ but still the initial disturbance has been reduced significantly.

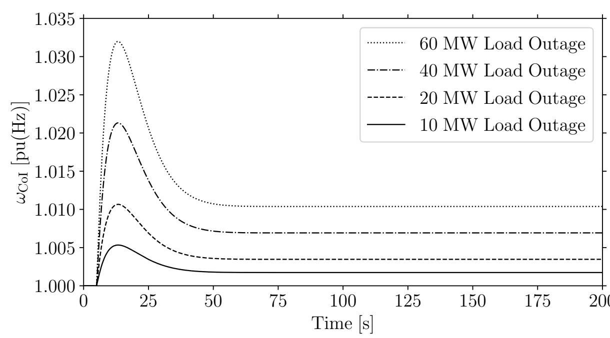

Fig. 6: Load outages with with no load control and no ESS.

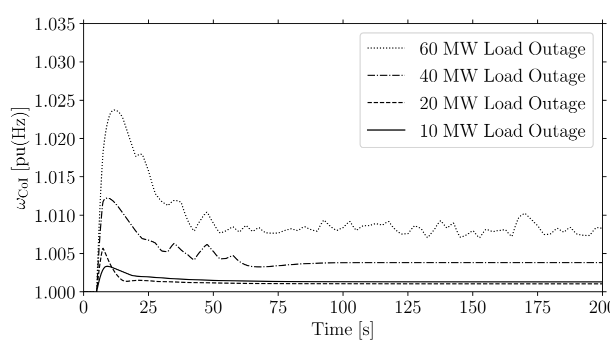

Fig. 7: Load outages with clusterised load control and ESS.

Figure 8 shows that the AGC is able to compensate the steady-state frequency error, which cannot be removed by the the proposed clusterised control with ESS.

Simulation results show that the proposed load control is quite useful for frequency improvements, however, other system variables such as voltage must not be neglected. For the 20 MW load outage scenario, the voltage is shown for three controller setups in Fig. 9. These setups are: (i) clusterised

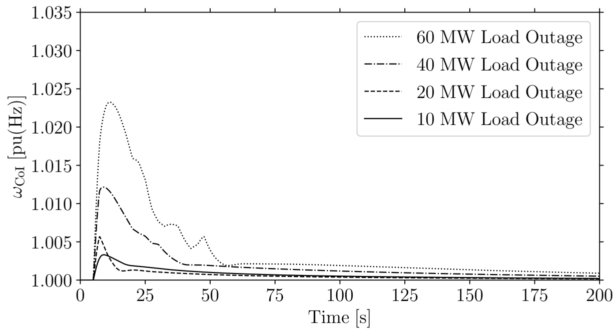

Fig. 8: Load outages with clusterised load control and ESS and conventional AGC.

controller with the ESS; (ii) ESS only; and (iii) clusterised controller without the ESS. As expected, the clusterised controller combined with an ESS has the best impact on the dynamic response of the system with the lowest initial disturbance and steady state settling point closest to the nominal value of 1 pu. The ESS alone shows a slightly higher steady state settling point whereas the clusterised controller alone shows a much lower steady-state value due to the increased switching events. It is also worth mentioning that the proposed controller reduces the absorbed energy of the ESS.

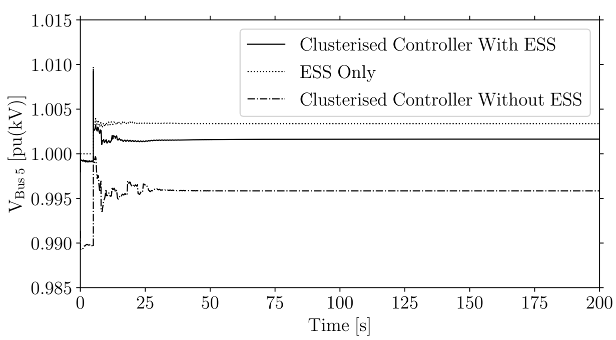

Fig. 9: Voltage at bus 5.

VI. Conclusions

This paper proposes a controller that consists in switching on/off flexible loads based on frequency measurements. Then the proposed controller is combined with an ESS to reduce the effect of discrete variations of the loads and allow for longer period during which the loads are on or off. Simulation results indicate that the proposed controller is effective and allows keeping the capacity of the ESS small without being detrimental to other variables in the system. We believe that this work poses the basis for interesting future developments, for example, a comprehensive analysis of the impact of granularity of discrete controllers.

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