

# An Adaptive Load Shedding Technique for Controlled Islanding

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**Abstract - The main contribution of this paper is the development of a novel load shedding methodology so as to regulate unacceptable frequency deviations, with least disruption of service, in the case of controlled islanding. To achieve this, an abstracted model of each islanded area, consisting of one lumped generator and turbine model, is used. Since in the controlled islanding the bounds of the areas are determined, a good estimation of the generation-load mismatch can be obtained. Taking advantage of the latter an amount of load to be shed in the load-rich areas, at the moment of the area separation is proposed. This amount is optimally selected so as to minimize the total load shed, taking into account the primary frequency control dynamics and the conventional Underfrequency Load Shedding schemes (UFLS). Markov Chain Monte Carlo (MCMC) methods and Model Predictive Control (MPC) are the two optimization tools that are used to solve the resulting optimization problem. The effectiveness of the proposed technique is evaluated via simulation on the IEEE 118 bus network.**

*Keywords - Load shedding, controlled islanding, model predictive control, randomized optimization methods.*

## 1 Introduction

As the operation of power systems is getting closer to its stability margins it is more likely for large disturbances to drive the system into a wide-area blackout through cascading events. Controlled islanding is a promising scheme that prevents the failure spreading in the rest of the system. The system is intentionally split into islands and consequently the generation-load balance is lost. If the magnitude of the imbalance is such that the primary frequency control is either slow or the reserves are not enough to maintain the frequency in the desired range, emergency control actions take place.

In the generation-rich island, generators may get tripped by the operator or in the end by protection devices rendering though the system closer to its nominal equilibrium point. The load-rich island is more crucial since a frequency drop of around 2.5-3 Hz can trigger the under-frequency generator protection and thus trip the generator. This leads to a larger generation-load mismatch and in the worse case, after a sequence of outages, to a total blackout. Hence appropriate load shedding schemes are essential for the load-rich areas.

Conventional UFLS methods are based on the frequency drop or also, in some cases, on the rate of the frequency deviation. The under-frequency relay settings are predefined according to the desired performance of the entire system and thus cannot assure the optimal amount of load shed in the case of islanding. Another issue is that

modern power systems are rich in distributed generation, which may lead to inefficient load shedding, since the load shedding action will also eliminate distributed sources of generation [1].

Main contribution of this paper is that it provides an adaptive load shedding technique for regulating unacceptable frequency fluctuations in the load-rich controlled islanded areas. This method utilizes the knowledge of the generator and load characteristics of the formed island in order to estimate the magnitude of the generation-load mismatch. That way, the average rate of change of the generator's frequency can be more accurately determined. Adaptive load shedding schemes based on the rate of frequency decline have been also used in [18], [19].

The proposed scheme is built under the assumption that loss of synchronism can be quickly detected and the control islanding is a centralized action that includes the fast detection of the coherent generators and determination of the borders of the islands. In [20] and [2] controlled islanding is set using coherency algorithms presented in [21] and determining also the boundaries via optimization algorithms for minimizing the resulting generation-load mismatch. However, the detection of loss of synchronism is obtained in a decentralized way. The increasing, though, development in Phasor Measurement Unit (PMU) technology and the communication infrastructure is promising that in the near future angular instability could be detected rapidly enough so as the information to be processed centrally.

For the design of an optimal load shedding policy an aggregated model of each island is used [15]. Low order frequency response model, so as to estimate the frequency behavior of a large power system, have been earlier presented by [17]. This consists of one generator, determined by the classical model, its turbine and governor dynamics. UFLS is also taken into account, since the described method does not cancel its scope but takes action centrally from a higher layer of the hierarchical monitoring and control structure.

The main idea of the proposed method is that at the time the borders of the islands are decided, instead of waiting for the UFLS to act, an initial amount of load shedding is applied. The risk of negative dynamic effects is also minimized by unloading the system immediately in the load shedding schemes focused in voltage stability, presented in [5]. In our method, the value is chosen so as to minimize the total amount of load shed, which is defined as the sum of the initial and any additional load that may be shed by the conventional UFLS action, over

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the dynamic response of the frequency. This is a typical optimization problem with linear but hybrid dynamics, and constraints imposed by physical limitations. The hybrid nature arises due to the conventional load shedding scheme and the saturation of the primary control. To solve this problem, two different methods are employed. The former is a randomized optimization technique, which is based on Markov Chain Monte Carlo methods [4], whereas the second is based on Model Predictive Control (MPC) [3]. The latter provides efficient theoretical and computational tools to solve optimization problems even online, by shifting the computational burden offline. More details regarding these optimization methods will be given in Section 3. The effectiveness of the proposed scheme is verified via simulations on the IEEE 118-bus network.

The remainder of the paper is organized as follows. In Section 2 a description of the models used is provided, whereas in Section 3 information regarding the adopted optimization techniques is given. Section 4 provides the simulation results obtained from the application of these methods on the IEEE 118-bus network. Finally, Section 5 provides some concluding remarks and directions for future work.

## 2 Physical description and mathematical modeling

As stated in the introduction, objective of this paper is to quantify the potential improvement, if an initial amount of load is shed, in the load-rich island, prior to the action of conventional UFLS, in the case where the network is divided into islands as an effect of a disturbance. To determine this amount of load, each island is represented by an aggregated model, consisting of the dynamics of a single generator with turbine and governor dynamics. The latter is reasonable, since the strong coupling of the coherent generators allows us to represent each area with a single unit, so as to estimate the frequency response of the system. Moreover, the discrete events, due to the conventional UFLS actions and the governor saturation, are also modeled, resulting in the hybrid system used in the optimization process. Figure 1 provides a block diagram, which illustrates the described technique.

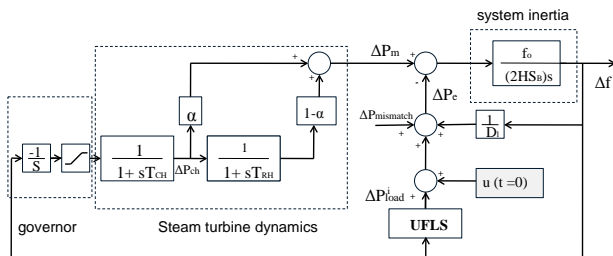


Figure 1: Block diagram of the aggregate model.

To derive such a model, we define the lumped area's swing equation as in [15]

$$\Delta \dot{f} = \frac{f_0}{2HS_B} (\Delta P_m - \Delta P_e), \quad (1)$$

where  $\Delta f$  denotes the deviation of the frequency from its nominal value  $f_0$ , and  $\Delta P_m$ ,  $\Delta P_e$  represent the deviation of the total mechanical and electrical power from their set points respectively. The parameters  $H$  and  $S_B$  are the so

called total inertia time constant and the total rating power, and are defined by

$$S_B = \sum_j S_{B_j},$$

$$H = \frac{\sum_j H_j S_{B_j}}{\sum_j S_{B_j}},$$

where  $j$  denotes the number of generating units inside the area.

By including also the turbine (a steam turbine with a reheating unit was used) and governor dynamics as shown in Figure 1, the overall system can be represented by

$$\begin{bmatrix} \Delta \dot{f} \\ \Delta \dot{P}_m \\ \Delta \dot{P}_{ch} \end{bmatrix} = \begin{bmatrix} \frac{f_0}{2HS_B} (\Delta P_m - \Delta P_{load}^i - \frac{1}{D_l} \Delta f - \Delta P_{mismatch} - u) \\ -\frac{1}{T_{RH}} \Delta P_m + (\frac{1}{T_{RH}} - \frac{a}{T_{CH}}) \Delta P_{ch} + \frac{a}{T_{ch}} \Delta P_p \\ \frac{1}{T_{CH}} (-\Delta P_{ch} + \Delta P_p) \end{bmatrix}, \quad (2)$$

where  $\Delta P_m$  and  $\Delta P_{ch}$  are denoted in Figure 1,  $T_{CH}$ ,  $T_{RH}$  are the turbine time constants,  $S$  is the speed droop of the primary controller, and  $D_l$  represents the frequency dependency of the load.  $\Delta P_{mismatch}$  denotes the initial mismatch between the generation and load in a controlled islanding area, whereas  $\Delta P_{load}^i$  denotes the amount of load shed up to stage  $i$  of the conventional UFLS, and will be described in the sequel.  $\Delta P_p$  captures the saturation of the primary controller, as shown in the block diagram. Specifically,

$$\Delta P_p = \begin{cases} \Delta P_p^{min} & \text{if } -\frac{1}{S} \Delta f \leq \Delta P_p^{min} \\ -\frac{1}{S} \Delta f & \text{if } \Delta P_p^{min} < -\frac{1}{S} \Delta f < \Delta P_p^{max} \\ \Delta P_p^{max} & \text{if } -\frac{1}{S} \Delta f \geq \Delta P_p^{max} \end{cases}$$

The block UFLS in Figure 1, stands for conventional Underfrequency Load Shedding, and could be thought of as a sequence of predetermined actions. More specifically, when the frequency drops below some thresholds, a certain value of load is shed. The values for the different stages of the conventional UFLS, that were used in the simulations are depicted in Table 1. Normally, there is also a delay in these switching actions, which for simplicity is not taken into account in this abstracted version of the network, but is modeled in the IEEE 118-bus system.

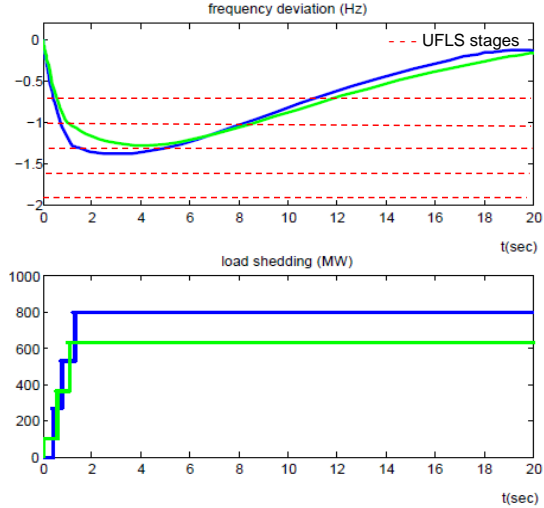
UFLS (conventional)	Stage 1	Stage 2	Stage 3	Stage 4
$\Delta f$ threshold(Hz)	-0.7	-1	-1.3	-1.6
Load shedding(pu)	10%	10%	10%	15%

Table 1: Stages of the conventional load shedding scheme.

The saturation of the primary controller and the various stages the conventional UFLS contributes to the hybrid nature of the system dynamics. More details about the different modes of operation are given in Section 3.2.

Variable  $u$  denotes the initial value of load shedding, that based on the description so far, will be determined via an optimization method. For illustrative purposes, Figure 2 depicts the frequency response of an example system and the corresponding load shedding behavior for the case

where  $u = 0\text{MW}$  (“blue”) and  $u = -100\text{MW}$  (“green”). These results were obtained based on MCMC optimization that will be described in the next section, but have been included here so as to get a qualitative idea of the behavior of the system (2), and the potential improvement afforded by performing an initial load shedding.



**Figure 2:** Frequency and total load shedding response based on the abstracted model.

### 3 Optimization techniques

#### 3.1 Randomized methods

Markov Chain Monte Carlo (MCMC) method is a randomized optimization technique, which explores the search space via a Markov chain. In this setting, the problem of optimizing a certain criterion  $J(u)$  is transformed to the problem of approximating its optimizer by extracting candidate solutions  $u$  from a proposal distribution of our choice. Variable  $u \in \mathbb{R}$  denotes the decision variable, which for the purpose of this paper represents the initial value of load that should be shed so as to minimize the total amount of load shedding. The algorithm involves then a sophisticated accept-reject mechanism, and hence the optimal  $u$  can be identified. The following algorithm summarizes the basic steps of the so called Metropolis-Hastings algorithm.

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#### Metropolis-Hastings algorithm

- 1: Let  $u_0$  denote an initial choice for  $u$ .
- 2: Define as  $N$  the total number of iterations.
- 3: **For**  $i = 0 : N$   
 Extract  $u_{i+1} \sim p_u(\cdot|u_i)$

$$\rho = \min \left\{ 1, \frac{p_u(u_i|u_{i+1}) J(u_{i+1})^\beta}{p_u(u_{i+1}|u_i) J(u_i)^\beta} \right\},$$

$$u_{i+1} = \begin{cases} u_{i+1} & \text{with probability } \rho, \\ u_i & \text{with probability } 1 - \rho, \end{cases}$$

**end**

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At each step  $i$  of the algorithm, the extracted variable  $u_i$  is accepted with a probability  $\rho$ , as this is defined in the algorithm above. Otherwise, it is rejected and the previous state of the chain is replicated. At the end of the algorithm, the extracted points are concentrated at different regions,

and based on the peakedness, the optimal value for  $u$  is determined.

For this example the objective function was chosen to be

$$J(u) = e^{\beta(\text{Total load shed})}, \quad (3)$$

where the total load shed is defined as the sum of  $u$  and the action taken by conventional load shedding techniques (UFLS). Variable  $\beta$  is a tuning parameter, and in a simulated annealing setting [6], as  $\beta$  increases the peakedness of  $J(u)$  is also increasing. The probability density  $p_u(\cdot|u_i)$  denotes the proposal distribution, which at the first step was chosen to be a uniform distribution, so as to search accurately the decision space. At a next step the entire process was repeated, this time by sampling from gaussian distributions centered at the accepted samples of the first run. That way, a local search was performed, and a more accurate optimizer was identified.

The main limitation of this method is that since it is a simulation-based process, and relies on sampling, it can not be applied for online optimization problems, and hence is limited to offline applications. Nevertheless, it was employed in the specific application due to the guarantees that it provides to converge to the optimum in low dimensional problems (only one decision variable in our case). Hence it serves as a benchmark, that allows us to compare the solution obtained by the following MPC scheme, which makes use of a linearized version of the model. Alternatively, in the absence though of theoretical guarantees, any other efficient heuristic (i.e. Genetic Algorithms) could be employed.

#### 3.2 Model Predictive Control

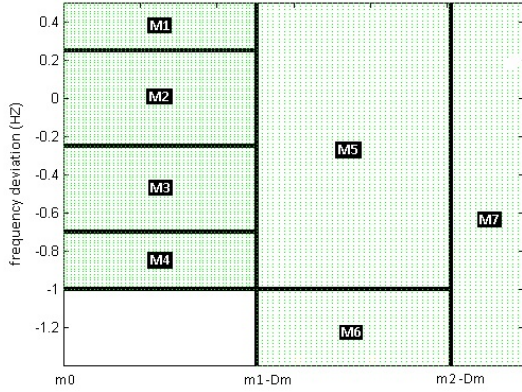
Model Predictive Control (MPC) provides an efficient way of solving optimal control problems [7]. In the case where both the model dynamics and the constraints are linear, and the cost is either linear or quadratic, the resulting optimization problem is a linear or quadratic program, and can be efficiently solved online.

Systems like the one described in Section 1, are governed by linear dynamics and include polyhedral constraints, but exhibit a hybrid behavior. For the load shedding case, this is due to the discrete modes introduced by the action of the conventional load shedding scheme, and the saturation of the primary frequency control. These systems are hence described by Piecewise-Affine dynamics, which are active over different partitions of the state space. Since MPC is formulated in discrete time [3], let

$$\begin{aligned} x(k+1) &= \tilde{A}_i x(k) + \tilde{B}_i u(k) + \tilde{\Gamma}_i, \\ y(k) &= \tilde{C}_i x(k) + \tilde{D}_i u(k) + \tilde{G}_i, \end{aligned} \quad (4)$$

denote the discretized version of (2), where  $[x(k) \ u(k)]^T \in P_i$ , and  $P_i$  denotes the partition  $i$ . Following the detailed description of [8], [9], the partitions  $P_i$  are characterized by the so called guard lines of the form

$$G_{i,x}x(k) + G_{i,u}u(k) \leq G_{i,c}. \quad (5)$$



**Figure 3:** Mode illustration of the piecewise-affine system.

For simplicity of notation, let  $m_i = \Delta P_{load}^i$  denote the amount of underfrequency load shedding up to stage  $i$  of UFLS. To formulate the system described in Section 1 in this framework, we augment the state space with an artificial state  $s(k+1) = m_i$ , where  $m_i$  corresponds to the total amount shed at each mode due to conventional UFLS. Figure 3 illustrates the proposed partition. The horizontal axis is the artificial state  $s$ , whereas the vertical axis denotes the frequency. At the modes  $M_1, M_2, M_3$ , where no load shedding action is taken, we have that  $s(k+1) = m_0 = 0$ . From these modes,  $M_2$  corresponds to the case where the saturations of the primary controller are not active, and  $M_1, M_3$  represent the case where the controller's output is saturated to the lower and upper limit respectively. When the frequency drops below  $-0.7\text{Hz}$  ( $M_4$ ), the first amount of load is shed, and hence  $s(k+1) = m_1$ . Then a discrete jump will be triggered instantaneously, and the system will operate at  $M_5$ , unless the frequency drops below  $-1\text{Hz}$ , where the system will operate at  $M_6$  ( $s(k+1) = m_2$ ). Similar reasoning can be used for the case of more load shedding stages.

Given this representation, let  $N$  denote the MPC prediction horizon. The only free control input is  $u(0)$ , as  $\{u(k)\}_1^N$  are restricted to be equal to  $u(0)$ , since  $u(0)$  represents the initial load shedding amount, which is then kept constant. The optimization problem can be then defined as

$$\min_{u(0)} J(N) = \min_{u(0)} |(s(N) + u(0))|, \quad (6)$$

subject to  $u_{min} \leq u(0) \leq u_{max}$  and the dynamics (4).  $u_{min}$  and  $u_{max}$  are selected over a reasonable region towards the goal of minimum load shedding. By  $s(N)$  we denote the amount of load shed at the end of the horizon  $N$ .

Non-standard cost functions, like (6), can be easily encoded in the MPT toolbox [8], which was used in this paper. The latter is due to the Yalmip interface, developed by [10], which allows to add arbitrary constraints and objective functions to an MPC setup.

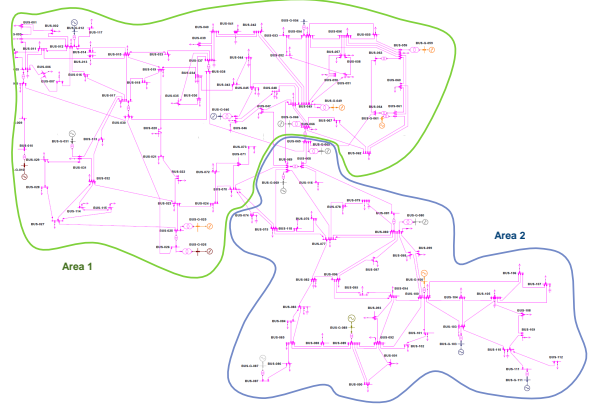
## 4 Computational analysis

### 4.1 Test system

The proposed technique is applied to the IEEE 118-bus network and time domain simulations are carried out so as

to demonstrate its effectiveness. This model is considered complex enough to capture the difficulties that may arise in a realistic scenario. The data of the model are retrieved from a snapshot available at [11]. Since there were no dynamic data available, typical values provided by [12] were used for the simulations. All generators are represented by the classical model and are also equipped with primary frequency control, Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS). The model of the IEEE 118-bus network is implemented in MATLAB by [14]. For more details on the generation data used, the reader is referred to [2]. The stages of the conventional UFLS that the entire network is equipped with, are described in Table 1. Two kind of delays are taken into account for these switching actions. Specifically, load shedding is triggered with 10 msec relay delay, given that the frequency has been already maintained below the specific threshold for at least 100 msec.

For the demonstration needs of the paper, we considered the IEEE 118-bus network to be divided in two areas according to the controlled islanding decision after a disturbance that leads to loss of synchronism. These two areas are illustrated in Figure 4 in Neplan environment [13] for better visualization.



**Figure 4:** IEEE 118-bus network.

From these two areas, Area1 is characterized by a generation deficit of 539.6 MW and hence Area 2 is a generation rich island with 539.6 MW generation excess. Since this paper is devoted in a under frequency load shedding study, Area 1 is represented by the abstracted model described in Section 2.1. Area 1 consists of the generators G10, G12, G25, G26, G46, G49, G54, G59, G61 and G66. The parameters of this abstracted model are summarized in the following table.

$S_B$ (MVA)	$H$ (s)	$P_{gen}$ (MW)	$P_{load}$ (MW)	$f_0$ (Hz)
2457.8	3.4509	2054	2593.6	50
$D_l$ ( $\frac{\text{Hz}}{\text{MW}}$ )	$S$ ( $\frac{\text{Hz}}{\text{MW}}$ )	$T_{CH}$ (s)	$T_{RH}$ (s)	$a$
0.0129	0.001	0.4	4	0.2

**Table 2:** Parameter values for the abstracted model of Section 2.

### 4.2 Optimization results

To determine the optimal value of  $u$ , the optimization methods described in Section 3, have been employed. For the MCMC algorithm, two stages were performed. The first comprises of 10000 random samples (chain of the distribution) extracted from a uniform distribution and 6354

states of this chain were accepted. At the next stage, another 10000 candidate solutions were extracted, this time from a gaussian distribution around the accepted states of the previous run, and 3562 states were accepted. The value of  $u$  that gave the higher performance was found to be  $u = -126MW$ .

For the MPC implementation, an explicit controller was calculated using the Multi-Parametric Toolbox (MPT) [8]. For the implementation, a time horizon of  $N = 10$  steps was used, the discretization step was fixed at  $T_s = 0.2 \text{ sec}$ , and  $u$  was considered to be constrained in  $-1138MW \leq u \leq 0MW$ . This minimum value corresponds to the total possible conventional load shedding action (for this case 45% of the load). The optimal choice of the values  $N$  and  $T_s$  is always a trade-off, but for this case no parametric study was conducted. The optimal value was found to be  $u \approx -150MW$ . Although MPC has the advantage that could be applied online, it may lead to a suboptimal solution due to the discretization error. Similarly, MCMC can determine only an approximate optimizer of the corresponding cost function since it is based on sampling. Nevertheless, for the specific case, where the decision space is one dimensional, MCMC may lead to high accurate solutions. In general, when applied to the realistic network, the value of  $u$  will only be suboptimal.

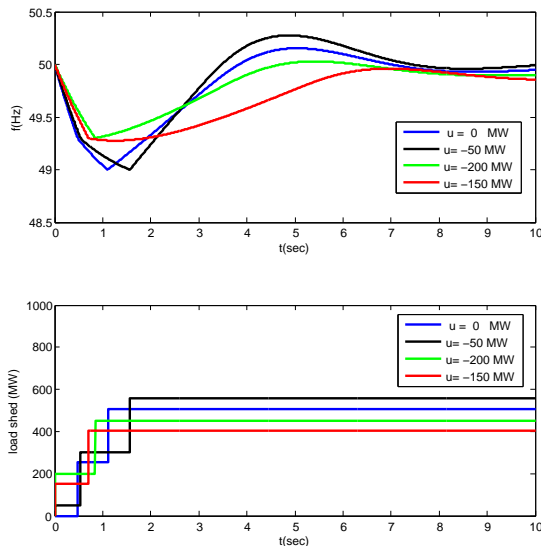


Figure 5: Area1 aggregate system frequency and load shedding response

### 4.3 Simulation results

Both the MCMC and MPC solutions were tested. For the simulations though shown in this subsection only the value generated from MPC was considered, even though MCMC led to better results. This was decided due to the fact that MPC has the potential to be applied online.

For illustrative purposes, Figure 5 shows the frequency and load shedding response of the abstracted system for the case where the optimal  $u = -150MW$  is applied. In the same figure, the outcome of the simulation results for  $u = -200MW$ ,  $u = -50MW$  and  $u = 0MW$  are also depicted, and as expected the optimal value for  $u$  leads to the minimum total load shedding value. Note that

$u = -50MW$  leads to a higher total amount of load shed compared to  $u = 0MW$ . This is due to the fact that in both case the same number of stages of UFLS are activated.

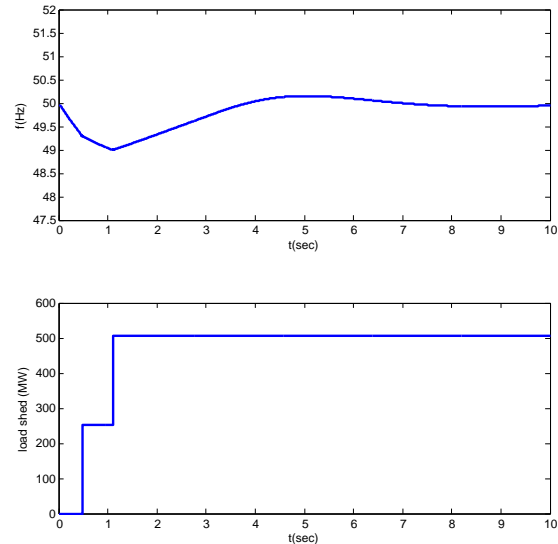


Figure 6: Area1 aggregate system frequency and load shedding response

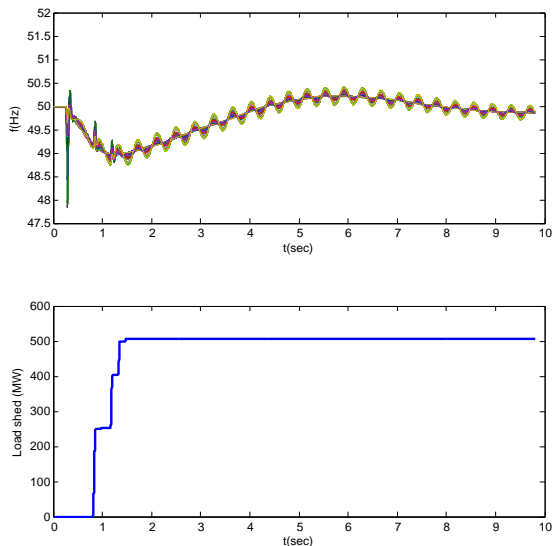
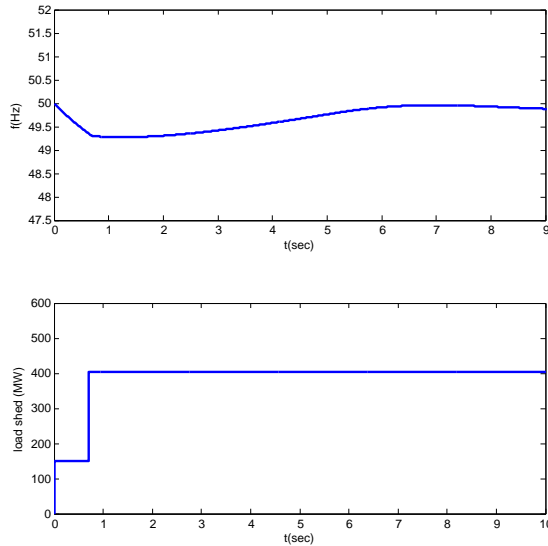


Figure 7: Area1 frequency dynamics and load shedding of the 118-bus system

For comparison purposes, the IEEE 118-bus network (splitted in two areas at 0.27sec) was simulated for the case of conventional load shedding ( $u = 0$ ). The results are depicted in Figure 7, where the upper plot shows the response of the frequencies of Area 1, and the lower figure illustrates the load shedding action. The response of this detailed system is compared with that of Figure 6, which corresponds to the same scenario for the abstracted version of the system though. The frequency trajectories of Figures 7, 9 represent the frequencies of the buses in Area 1, and those that exhibit high transient behavior at the splitting instance correspond mainly to the buses at the end of the tripped lines. The duration that the frequencies are initially below the UFLS frequency thresholds is less than 100 msec and for that reason conventional load shedding stages are not activated. It should be also noted, that Figures 7, 9 are slightly shifted to the right compared to those

of Figures 6, 8, since the IEEE 118 network was splitted in two areas at 0.27 sec. It is clear that the aggregate system captures quite accurately the behavior of a complex network, and apart from some oscillations, their average responses are almost identical.



**Figure 8:** Area1 aggregate system frequency and load shedding response with 150MW initial load shedding

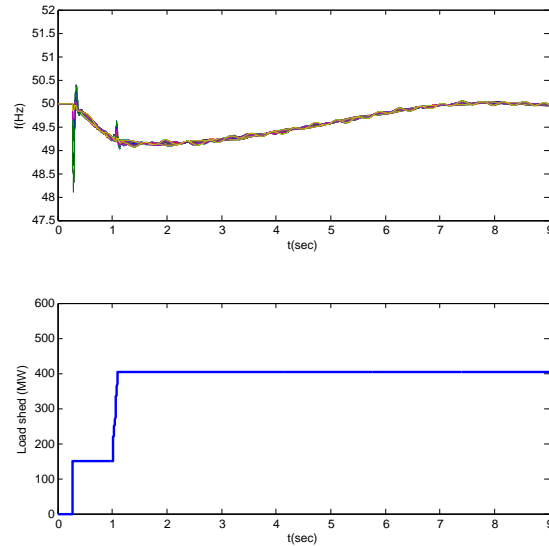
The same study was repeated, this time by applying an initial amount  $u = -150MW$  of load shedding, which was found to be optimal by the MPC algorithm. Note that this is applied at 0.27sec, when the system is divided in two areas. The results of the detailed and the lumped system are reported in Figures 9 and 8 respectively. Once again, the abstracted system and the IEEE 118-bus network exhibit a very similar behavior. Moreover, this simulation serves as a proof of concept of this paper, since application of the optimal  $u$  designed based on a simplified model, managed to reduce the total amount of load shed to 20.3%, in a realistic simulation environment. It should be also remarked, that the total amount of load shedding for the two cases is almost identical.

## 5 Conclusion

In this paper a novel load shedding methodology is presented. The problem of identifying an initial amount of load, which will be shed immediately after the decomposition of the network into islands, was investigated. To determine the optimal load shedding value, optimization techniques based on MPC and Monte Carlo methods for an abstracted model equipped with a conventional load shedding mechanism, were employed. The outcome of this method was applied to the IEEE 118-bus network, and time-domain simulations were carried out. The results indicate a potential improvement compared to conventional approaches.

Similar arguments hold also for the over-frequency case. It is then proposed that the generation to be shed will preferably belong to distributed units so as to reduce the restoration time compared to big power plants. As stated also in [16], this is feasible under the assumption of future networking in the distribution level which allows in-

dependent manipulation of the distributed generation and the actual loads.



**Figure 9:** Area1 frequency and load shedding response with 150MW initial load shedding

In future work, we plan to extend the aggregate model so as to capture more accurately the response of the real system. On the one hand a more detailed model for the turbine (i.e considering also valve speed saturation) could be employed in the one mass system representation. On the other hand, one could also consider the fact that in a realistic case the islanded area may consist of generators with different control systems and/or turbine dynamics. The “similar” ones could be then lumped into one aggregate model. The latter will lead to an abstraction with more than one generators connected with each other according to the reduced admittance matrix of the islanded network.

Moreover, this approach will be tested exhaustively via simulations for both load-rich and generation-rich islands for various disturbances that lead to the need of controlled islanding, in order to collect statistics regarding its performance. Another issue is to adopt a receding horizon implementation in the MPC setting, instead of optimizing only over the initial load shedding value. The latter will provide feedback in the design process and hence it will account for model mismatch and parameters uncertainties.

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## REFERENCES

- [1] “IEEE guide for the application of protective relays used for abnormal frequency load shedding and restoration”, IEEE Std C37.117-2007, pp. c143, Aug. 2007.
- [2] S. Koch, S. Chatzivasileiadis, M. Vrakopoulou and G. Andersson, (2010) “Mitigation of cascading fail-

- ures by real-time controlled islanding and graceful load shedding”, IREP Symposium, Bulk Power Systems Dynamics and Control, VIII, pp. 1 -19
- [3] A. Bemporad and M. Morari, (1999) “*Robust Model Predictive Control: A Survey*”, Lecture Notes in Control and Information Sciences, Springer Berlin / Heidelberg.
- [4] C. P. Robert and G. Casella, (2004) “*Monte Carlo Statistical Methods*”, Springer.
- [5] S. Arnborg, (1997) “*Emergency control of power systems in voltage unstable conditions*”, PhD dissertation, KTH Royal Institute of Technology.
- [6] A. Lecchini, J. Lygeros and J. Maciejowski, (2010). “*Stochastic optimization on continuous domains with finite-time guarantees by Markov chain Monte Carlo methods*”, IEEE Transactions on Automatic Control, to appear.
- [7] J. Maciejowski, (2002). “*Predictive Control with Constraints*”, Prentice Hall, London.
- [8] M. Kvasnica, P. Grieder, M. Baotic and F.J. Christophersen (2006). “*Multi-Parametric Toolbox (MPT)*”, Technical report, ETH Zürich.
- [9] A. Bemporad, F. Borelli and M. Morari (2000). “*Optimal controllers for hybrid systems; stability and piecewise linear explicit form*”, IEEE Control and Decision Conference, Australia.
- [10] J. Löfberg (2004). “*A toolbox for modeling and optimization in MATLAB*”, CACSD Conference, Taiwan.
- [11] “*Power Systems Test Case Archive*”, , College of Engineering, University of Washington. URL: <http://www.ee.washington.edu/research/pstca/>.
- [12] P. M. Anderson and A. A. Fouad (2002). “*Power System Control and Stability*”, IEEE Computer Society Press.
- [13] NEPLAN Official Website. <http://www.neplan.ch>.
- [14] T.H. Demiray (2008) “*Simulation of Power System Dynamics using Dynamic Phasor Models*”, PhD thesis, Diss. ETH No. 17607, available online from ETH Zurich, Switzerland
- [15] G. Andersson (2009), “*Dynamics and Control of Electric Power Systems*”, Lecture notes, ETH Zürich.
- [16] S. Hirodantis and H. Li (2009). “*An adaptive load shedding method for intentional islanding*”, International Conference on Clean Electrical Power.
- [17] P.M. Anderson and M. Mirheydar (1990), “*A Low-Order System Frequency Response Model*”, IEEE Transactions on Power Systems, Vol.5, No.3.
- [18] H.You, V. Vittal (2003). “*Self-Healing in Power systems: An Approach Using Islanding and Rate of frequency Decline-Based Load Shedding*”, IEEE Transactions on Power Systems, Vol.18, No.1.
- [19] V.V. Terzija (2006). “*Adaptive Underfrequency Load Shedding Based on the Magnitude of the Disturbance Estimation*”, IEEE Transactions on Power Systems, Vol.21, No.3.
- [20] H. You, V. Vittal, and X. Wang (2004), Slow coherency-based islanding. Power Systems, IEEE Transactions on, vol.19, no.1,pp.483 - 491
- [21] J. H. Chow (1982), Time-Scale Modeling of Dynamic Networks with Applications to Power Systems. New York: Springer-Verlag, vol. 46.