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Power Systems Emergency Control

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Abstract

The requirement for improved efficiency whilst maintaining system security necessitates the development of improved system analysis approaches and the development of advanced emergency control technologies. Load shedding is a type of emergency control that is designed to ensure system stability by curtailing system load to match generation supply.

This report presents a new adaptive load shedding scheme that provides emergency protection against excess frequency decline, while minimizing the risk of line overloading. The proposed load shedding scheme uses the local frequency rate information to adapt the load shedding behaviour to suit the size and location of the experienced disturbance. The proposed scheme is tested on a 3-region, 10-generator sample system and shows good performance.

Keywords: Emergency Control, Cascade Failure, Inter-region Power Flow, Load Shedding.

Notation

N_X and N_Y	number of dynamic and algebraic variables, respectively
N_G and N_L	number of generation and load buses, respectively
N_R and N_O	number of power system regions and operating points, respectively
N_E	number of generation events requiring protection
x_t, y_t, and $x(i)$, $y(i)$	power system dynamic and algebraic variables (at time *t*, and at O^i, respectively)
G_t, $G(i)$, G and G^F	N_G vectors of inject power (at time *t*, at O^i, pre and post-fault, respectively)
G^i, and G^{iF}	injected powers in region *i* (pre and post-fault, respectively)
ΔG^i	N_G vector of lost generation in event $i \in N_E$
L_t, $L(i)$, L	N_L vectors of load demand (at time *t*, at O^i, and pre-fault, respectively)
L^i	load demand in region *i*
$\Delta L = [\Delta L^1, \cdots, \Delta L^{N_L}]$	N_L vector of load shed amounts
$O^i = [x(i), y(i), G(i), L(i)]$	power system operating points, where $i \in N_O$
$S_{ij} = P_{ij} + jQ_{ij}$	complex power flow between region $i \in N_R$ and region $j \in N_R$
Δ_{ij}	power flow constraint between region $i \in N_R$ and region $j \in N_R$
C	N_R vector of per unit impact factors
u_{ls} and u_{ls}^*	load shedding decision and optimal load shedding decision, respectively
ω_i^i	frequency in region $i \in N_R$ at time *t*
$\omega_{thr} = [\omega_{thr}(1), \cdots, \omega_{thr}(M)]$	vector of frequency thresholds
α, $\dot{\omega}_{0ff}$ and $\dot{\omega}_{thr}$	bias rate, threshold bias and major event threshold, respectively
$\dot{\omega}_0$	initial post-contingency frequency rate
ω_{LS}	earliest load shedding frequency
H	equivalent inertia constant,
D	equivalent damping coefficient,
T_{ij}	tie-line synchronizing coefficient between region *i* and region *j*,
T_g	governor time constant,
T_t	turbine time constant,
R_i	droop characteristic,

1. Introduction

Increasing economic pressures for power system efficiency and reliability have led to a requirement for the operation of secure power systems closer to their capacity limits [1, 2]. Yet, increased utilization of a system's generation and transmission assets tends to decreases system security, and increases the risk of complicated failure mechanisms [1]. Therefore, the requirement for improved efficiency whilst maintaining system security necessitates the development of improved system analysis approaches and the development of advanced emergency control technologies. This paper makes contributions in the last of those areas by proposing a new adaptive load shedding scheme.

Load shedding is an emergency control action designed to ensure system stability by curtailing system load to match generation supply. Typically, load shedding protects against excessive frequency or voltage decline by attempting to balance real and reactive power supply and demand in the system. Typical implementations involve decentralized load shedding control approaches where local shedding decisions, based on local information, are independently made through-out the system, rather then centralized control decisions based on overall system information.

The most common decentralized load shedding schemes are the under frequency load shedding (UFLS) schemes, which involve shedding predetermined amounts of load if the frequency drops below specified frequency thresholds [3]. Under voltage load shedding (UVLS) schemes, in a similar manner, are used to protect against excessive voltage decline. Various modified UFLS schemes have been promoted in support of improved protection, including: adaptive UFLS schemes that utilized both local frequency and frequency rate information [4, 5], dynamic UFLS schemes that dynamically adjust the size of load shed stages [3], and optimized UFLS schemes [6], amongst others. Unfortunately, the type of protection provided by these schemes is not co-ordinated with other aspects of the power system operation.

Recent cascade failure events have highlighted the importance of the complicated interactions between various aspects of a power system [1, 7-11]. These recent events have helped to identify hidden failure and line overloading as two important propagation mechanisms in cascade failure [7-10]. In particular, overloaded lines can contribute to cascade failure through a variety of mechanisms including: increased risk of flashover faults [10]; decreased synchronizing power causing transient instability or the unstable growth of small-signal power oscillations [24]; and heavy reactive power flows inducing transient voltage instability [7, 10, 12]. Similarly, the significant destabilizing influence of zone 3 relays during heavily reactive power loading was demonstrated in the 2003 North American cascade blackout event [1, 7, 12].

In recent years, numerous avenues for reducing cascade failure risks have been identified, including: general minimization of fault risks [12], the exploitation of flexible ac transmission systems and HVDC links [1, 10, 12], and improved, more coordinated emergency controls [1, 7, 10, 12]. In general terms, these suggestions are attempts to improve co-ordination of power system design and operation to decrease cascade failure risks caused by line overloading and large reactive power transfers. One key example is improved consideration of cascade failure issues in the automatic or manual decisions undertaken during emergency situations.

A renewed investigation of the load shedding for frequency protection is necessary because decentralised load shedding can actually induce temporarily overloaded power lines and/or increase voltage support requirements [10, 13]. Although there are many important aspects in the cascade protection problem, we will limit our investigation to load shedding protection of frequency.

Wide-area, or centralized, load shedding approaches appear to be one obvious candidate framework for developing load shedding schemes that offer better co-ordination with other cascade failure considerations [1, 5, 13-18]. Numerous wide-area load shedding studies have demonstrated the role of disturbance size and location, load shedding size and location, and shed delay time in the effectiveness of load shed actions [7, 10, 13, 15]. However when suitable, local approaches are still desirable due to reliability and cost issues [7].

In this work we propose a decentralized load shedding approach that mimics wide-area approaches to provide emergency protection against excess frequency decline but also provides protection against line overloading, and hence minimizes cascade failure risks. A key feature of the proposed load shedding scheme is the use of local frequency rate information to adapt the load shedding behaviour to the size and location of the experienced disturbance. Although frequency rate based load shedding schemes have previously been proposed [5, 14], our contribution is novel for two reasons: our use of local frequency rate information to protect wide-area quantities such as inter-region power flows, and the particular manner in which we utilize frequency rate information.

This report is organized as follows: In Section 2, a power system dynamic model is introduced and various assumptions are made. In Section 3, a centralized regional constrained load shedding problem is proposed and a solution developed. In Section 4, the key features of the centralized solution are used to motivate a suitable adaptive load shedding scheme for regional protection. In Section 5, simulations studies are provided that demonstrate the performance of our proposed scheme. Finally, in Section 6, some conclusions are made.

2. Power System Dynamics and Cascade Failure

In this section we introduce a modified power system model and introduce a number of definitions and assumptions. We then investigate the effect of load shedding on cascade failure mechanisms.

2.1 Power System Dynamics

At time t, consider the following non-linear differential-algebraic equation (DAE) that is an adaptation of the classical representation of power system dynamics [17, 18]:

$$\begin{aligned} \dot{x}_t &= f(x_t, y_t, G_t, L_t) \\ 0 &= g(x_t, y_t, G_t, L_t) \end{aligned} \tag{1}$$

where x_t is a N_X-dimensional vector containing dynamic variables such as relative rotor angle and angle rate, y_t is a N_Y-dimensional vector of algebraic variables such as nodal voltages, G_t is a N_G-dimensional vector of the injected power, and L_t is a N_L-dimensional vector of demand load. The typical non-linear DAE model often suppresses the dependence on G_t and L_t, but we will highlight the role of these disturbance and control variables, respectively, in our problem.

The power system may be required to satisfy a number of additional constraints (such as voltage limits or supply constraints):

$$\begin{aligned} &h_i(x_t, y_t) = 0 \quad \text{for } i = 1, \cdots, N_h \\ &\overline{h}_j(x_t, y_t) \le 0 \quad \text{for } j = 1, \cdots, \overline{N}_h \end{aligned} \tag{2}$$

where N_h and $\overline{N}_h$ are the number of equality and inequality constraints respectively. Our disturbance and control variables G_t and L_t will also be constrained in a number of natural ways (non-negative and non-increasing).

In this paper we consider frequency protection against the following types of events:

Definition 2.1 (*A N − 1 Contingency Event*) *A N − 1 contingency event is an unplanned generation loss event (or equivalent) for which the system is expected to remain stable without the application of an emergency control.*

Definition 2.2 (*A Protected Event*) *A protected event is a large unplanned generation loss event (or equivalent) for which the system is expected to remain stable, perhaps following the application of an emergency control action. For the purposes of this paper, we will also divide protected events into* minor protected *and* major protected *events according the risk of inducing overloaded lines.*

The following assumptions will hold throughout the remainder for the paper:

A1) Without loss of generality, we will assume that each region in the power system can be represented by single machine equivalents [2]. We let N_R denote the number of regions in a power system and we assume that $N_G = N_R$ and $N_L = N_R$.

A2) We assume that N_O candidate operating points $\{O^i\}$ are provided. Here, for $i = 1, \cdots, N_O$, $O^i = [x(i), y(i), G(i), L(i)]$ is a 4-triple of quantities, where $x(i)$ is a N_X-vector, $x(i)$ is a N_X-vector, $G(i)$ is a N_R-vector and $L(i)$ is a N_R-vector.

A3) We assume that a list of $N - 1$ contingency events and protected events is provided. For example, we might consider N_E possible unplanned generation events represented by N_R-vectors $\{\Delta G^i\}$ for each $j = 1, \cdots, N_E$. That is, if operating at O^i and event *j* is experienced, then the post-event generation power supply would become the N_R-vector $G^{iF} = G^i - \Delta G^i$.

A4) We assume that there are no voltage stability issues.

We let $S_{ij} = P_{ij} + jQ_{ij}$ denote the complex power flow between regions *i* and *j*. Then we define the following additional power system property.

Definition 2.3 (Δ*-Regionally Loaded*) *Suppose that a set* $\{\Delta_{ij}\}$ *of power flow constraints is specified. We will say that the power system is* Δ*-regionally loaded if:*

- *The system is stable, and*
- *The inter region power flows are constrained so that* $|S_{ij}| \leq \Delta_{ij}$ *for all* $i, j \in [1, \cdots, N_R]$.

Remarks:

1. Assumption A1 is made to simplify presentation and corresponds to an assumption that load shedding decisions can be made on a regional basis. This assumption seems no worse than the assumption typically used to motivate UFLS schemes. For example, in [6] it is assumed that the whole power system can be represented by a single machine equivalent (a system frequency response model). This assumption is relaxed in later simulation studies.

2.2 Cascade Failure and Line Overloads

Emergency control design approaches have typically been based on the assumption that contingency events are rare and have independent probabilities. That is, the possibility of simultaneously contingency events can safely be ignored. However, experiences through-out the world [1] and examinations of historic power system contingency data [11] demonstrate that contingency probabilities are not independent, and the possibility of multiple contingencies cannot be safely ignored. Cascade failure is one important multiple contingency failure mode that has been emphasized by recent system events [1, 7-11].

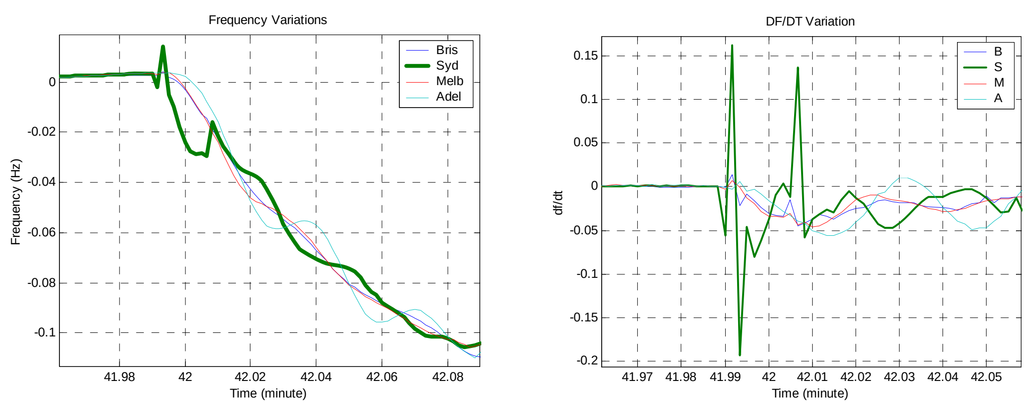
Unfortunately from a cascade failure perspective, standard UFLS schemes tend to share load shedding responsibilities through-out the system. This sharing behaviour arises as a natural consequence of a power system's tendency to distribute power adjustments though-out the system according to the machine inertias (although the initial impact of any disturbance tends to be initially distributed according to synchronizing power coefficients) [5]. This load sharing behaviour is undesirable from the perspective that overloaded lines have been identified as an important source of the observed cascade failure behaviour [7-9]. In comparison, recently proposed wide-area load shedding scheme have demonstrated that the optimal action is often to rapidly shed load near the source of power imbalance, and hence minimizes the impact on inter region power flows [10, 13, 15].

This suggests that there are two basic paradigms for load shedding: a shared load shedding paradigm, and a targeted load shedding paradigm. The first paradigm appears in the well-known UFLS schemes, and the second paradigm appears in some recently proposed wide-area load shedding approaches.

Using simulations for a multi-region power system (as shown in Section 5), it is easy to illustrate the difference between these two paradigms, following generation loss in one region. Although both shared and targeted load shedding schemes may be able to stabilize overall system frequency, the shared load shedding response leads to a situation requiring more the power transmission requirements. In some situations, this increased power flow might cause line overloading and increase the risk of cascade failure.

Recalling recent real-world power system serious events demonstrate this fact, clearly. In Australian network, National Electricity Market Management Company (NEMMCO) coordinates the National Electricity Market (NEM) and states that the policy is to share the load shedding requirements. Fig. 1 shows the regional power system frequency and its rate deviations in four region centres following a significant incident on Friday 13 August 2004 in Australia. An equipment failure in New South Wales (NSW) led to the loss of six major electricity generating units in that region, resulting in some customers in NSW, Queensland, Victoria and South Australia losing supply. For this event, approximately 1500 MW of customer load was automatically shed from the system and power was progressively restored within 2.5 hours of the incident occurring [19].

Of particular significance, we note that load shedding in Queensland and the resulting increased transfer to NSW almost caused line overload and line trip events. A better load shedding strategy, such as selected load shedding in NSW could have significantly reduced the risk of reaching transfer limits, tripping of more generators and further cascade events. The initial frequency gradient strongly suggests that NSW had the fastest initial acceleration and a biased shedding approach for NSW could be used to significantly increased load shedding in that state. Analysis of this event show that regional load shedding is desirable and feasible and, in this situation, would have limited the peak stresses on interconnections.



(a) (b)

Fig. 1: Regional frequency response following a major protected event (the 13 August event in the main cities Brisbane, Sydney, Melbourne and Adelaide of the affected regions; a) frequency deviation, b) frequency gradient.

Remarks:

1. Sharing load shedding responsibilities (such as induced by UFLS) is not necessarily an undesirable feature and can be justified on a number of grounds. For example, shared load shedding schemes tend to improve the security of the interconnected regions by allowing generation reserve to be shared. Further, UFLS approaches can be indirectly used to preferentially shed the least important load in system. However, sharing load shedding can have a significant impact on inter region power flows and, in certain situations, might increase the risk of cascade failure.

2. In weakly inter-connected power systems, due to the delay in the propagation of frequency changes through-out the power system, there is some tendency for localization of power adjustments following large events. The size and delays of load shedding actions through the system depends on both the electrical distance and the inertias of the regional generation involved [5].

3. Centralized Regional-based Load Shedding

In this section, as a stepping stone, we investigate an idealized optimal centralized load shedding problem for an interconnected power system. Under our standing assumptions, and ignoring power losses, we consider the power system described by (1) and the following emergency control cost:

$$c(u_{ls}) = \sum_{i=1}^{N_R} C_i \Delta L^i(u_{ls}) \tag{3}$$

subject to the constraint that the system be Δ-regionally loaded. Here $C = [C_1, \cdots, C_{N_R}]$ is a vector of per unit impact factors, and $\Delta L^i(u_{ls})$ is the load change in the region i following load shedding decision u_{ls}. We let $L^i(u_{ls}) = L^i - \Delta L^i(u_{ls})$ denote the new load level in region *i*.

This cost function penalizes load shedding decisions in weighted proportion to the amount of load shed, whilst the constraint ensures system stability and no overloading of inter-region power lines. Other representations of the combined stability and power flows objectives are possible (for example, a quadratic penalty on inter region power flow, rather than a constraint on inter region power flow). Alternative representations of load shedding costs are provided in [6], but the additional features in these representations are not important in the context of this paper.

We now propose our centralised regional constrained load shedding control problem. Consider the system dynamics (1) and emergency cost (3). Following a protected event, our optimal centralized load shedding design problem is to determine the load shedding amounts $\{\Delta L^1, \cdots, \Delta L^{N_R}\}$ that minimize the cost (3).

3.1 The Two Region Emergency Control Problem

We now consider a simplified two-region load shedding problem. Here the Δ-regionally load constraint becomes a generation-load balance equation together with a power flow constraint (that is, $G^1 + G^2 = L^1 + L^2$ and $\left|G^1 - L^1\right| \leq \Delta_{12}$), where G^i is the generation in region *i*. That is, ignoring losses, total system generation must equal total system load, and the generation-load imbalance in either region must not exceed the inter-region power flow limits.

Our regionally based emergency control problem is to determine optimal load shed amount $\Delta L_1(u_{ls})$ and $\Delta L_2(u_{ls})$ that minimizes customer impact in the sense of achieving

$$\min_{u_{ls}}\{C_1 \Delta L^1(u_{ls}) + C_2 \Delta L^2(u_{ls})\} \tag{4}$$

subject to the Δ-regionally loaded constraint:

$$\begin{aligned} &G^{1F} + G^{2F} = L^1(u_{ls}) + L^2(u_{ls}), \\ &\left|G^{1F} - L^1(u_{ls})\right| \leq \Delta_{12} \end{aligned} \tag{5}$$

where G^{1F} and G^{2F} denote the post-event generation levels. We let $G^F = G^{1F} + G^{2F}$ denote the total post-event generation and let $\Delta G^F = (G^1 + G^2) - (G^{1F} + G^{2F})$ denote the total change in system generation.

3.1.1 Optimal Solution for Two Region Problem

This constrained optimization problem has only one degree of freedom, due to our power balance equation $\Delta L^1(u_{ls}) = \Delta G^F - \Delta L^2(u_{ls})$. Further, the linear nature of the cost ensures that if an optimal solution to the constrained problem exists, then a solution can be found at a constraint boundary. Rearrangement of constraints and some algebra gives the following optimal solution.

If load losses in region 2 cause larger customer impact, that is $C_2 > C_1$, then an optimal emergency control action, u_{ls}^* , is given in terms of the optimal load levels as

$$L^1(u_{ls}^*) = \begin{cases} \max\{G^{1F} - \Delta_{12}, 0\} & \text{if} \quad (G^F - L^2) < \max\{G^{1F} - \Delta_{12}, 0\} \\ G^F - L^2 & \text{otherwise} \end{cases} \tag{6}$$

$$\Delta L^2(u_{ls}^*) = \Delta G^F - \Delta L^1(u_{ls}^*) \tag{7}$$

and it also follows that $\Delta L^1(u_{ls}^*) = L^1 - L^1(u_{ls}^*)$ and $\Delta L^2(u_{ls}^*) = L^2 - L^2(u_{ls}^*)$.

Alternatively, if load losses in region 1 cause large customer impact, that is if $C_1 > C2$, then an optimal emergency control action, u_{ls}^* , is given in terms of the optimal load levels as

$$L^2(u_{ls}^*) = \begin{cases} \max\{G^{2F} - \Delta_{12}, 0\} & \text{if} \quad (G^F - L^1) < \max\{G^{2F} - \Delta_{12}, 0\} \\ G^F - L^1 & \text{otherwise} \end{cases} \tag{8}$$

$$\Delta L^1(u_{ls}^*) = \Delta G^F - \Delta L^2(u_{ls}^*) \tag{9}$$

Of primary interest, we note that this emergency control load shedding rule exhibits two distinct regions of behaviour. When operating inside the power flow constraints (ie. $\left|G^1 - L^1\right| \leq \Delta_{12}$), then it is optimal to shed the cheapest load. If the power flow constraint is reached (ie. $\left|G^1 - L^1\right| = \Delta_{12}$), then the ability to share load shedding has been reach and the remaining load must be shed in the more expensive region.

4. Decentralized Regional Load Shedding

The above centralized load shedding solution suggests that load shedding schemes that protect inter-region power lines should exhibit three distinct regimes of behaviour. The first regime of desired behaviour is a no load shedding response to $N-1$ contingencies events. The second regime is a shared load shedding behaviour in response to minor protected events. Finally, the third regime is a targeted load shedding behaviour in response to major protected events (so that changes to inter-region power flows are minimized).

In decentralized approaches the size and location of disturbances is not directly known. However, in [5, 14] it is shown that disturbance size is related to the average frequency rate experienced in the system. Moreover, local frequency change is related the electrical distance from the disturbance [5]. Further, in [10, 13], inter-region power requirements are minimized by shedding load near to the source of generation-load imbalance. Together, these three results suggest that local frequency rate information might be useful in targeting load shedding to the disturbance location, and minimizing inter-region power flows.

We use this idea to propose the following adaptive load shedding scheme for regional protection. Let ω_t^i denote the local frequency in region *i* at time *t*, and assume that the power system allows *M* fixed blocks of load shedding in each region. Our proposed load shedding algorithm is to shed load block *j* in region *i*, if at time *t*

$$\omega_t^i \leq \omega_{thr(j)}, \quad \text{for } j=1,\ \ldots,\ M \tag{10}$$

where

$$\omega_{thr(j)} = \min\{\omega_{thr(j)}^{0} + \dot{\omega}_{off}, \omega_{LS}\} \tag{11}$$

Here $\omega_{thr}^{0} = [\omega_{thr}^{0}(1), \cdots, \omega_{thr}^{0}(M)]$ is a vector of UFLS thresholds used to define the load shedding behaviour in response to minor protected events, ω_{LS} prevents unnecessary load shedding in response to minor frequency adjustments, and $\dot{\omega}_{off}$ is an offset used to bias load shedding towards the location of generation-load imbalance, if a major protected event is experienced. Here, the threshold bias $\dot{\omega}_{off}$ is given by

$$\dot{\omega}_{off} = \begin{cases} \alpha\dot{\omega}_0 & \text{if} \quad \dot{\omega}_0^i \geq \dot{\omega}_{thr} \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

where $\dot{\omega}_0^i$ is the initial post-contingency frequency rate experienced in power system region *i*, the gain α describes the bias rate towards the location of generation-load imbalance during major protected events, and $\dot{\omega}_{thr}$ is a major event threshold used to discriminate between minor and major protected events.

Connections with the approach of [5] become apparent when considering the scheme's block diagram shown in Figure 2. Both schemes involve the use of frequency rate information to modify frequency thresholds. However, the subsumption approach of [5] involves a switch between 2 sets of threshold values, whilst our approach involves a proportional change to thresholds values driven by the size of the disturbance. Further, our desire to minimize inter-region power flows whilst ensuring stability (rather than an exclusive focus on minimal frequency deviation) motivates our use of threshold adjustments based on initial frequency rates $\dot{\omega}_0^i$ (rather than the frequency rates $\dot{\omega}^i$).

Acceptable $\dot{\omega}_0^i$ estimation techniques may be system dependent (for example, may depend on the measurements available), but a reasonable $\dot{\omega}_0^i$ estimate is the maximum frequency rate within a short time window surrounding a significant frequency excursion event.

4.1 Design of Load Shedding Settings

The three key parameters of the proposed scheme are: the UFLS thresholds $\omega_{thr(j)}^0$ for $j = 1, \ldots, M$, the major event threshold $\dot{\omega}_{thr}$, and bias gain α. To simplify this process, it is important to recognize that parameter tuning can be conducted in three stages. The first stage would be the selection of $\omega_{thr}^0(j)$ by evaluating performance against the $N-1$ contingencies and minor protected events (in much the same way as existing UFLS settings can be designed). The second stage would be to determine a suitable $\dot{\omega}_{thr}$ by examining the initial frequency rate experienced by the system in response to a selection of minor and major protected events. In the third and final stage, a suitable α gain could be determined by variation until the scheme provides suitable protection against major protected events.

A structured design path is based on optimization techniques to determine ω_{thr}^0 and α. For example, suitable UFLS settings $\omega_{thr}^0(j)$ could be determined using an optimization approach such as [6]. Once ω_{thr}^0 and $\dot{\omega}_{thr}$ have been selected, a suitable gain α can be determined using a modification of the optimization approach used to obtain $\omega_{thr}^0(j)$ settings.

Remarks

1. The $\dot{\omega}_{thr}$ threshold choice delineates load shedding between "shared" and "targeted" behaviours. Hence, this threshold indirectly determines the amount of power importation allowed between connected regions.

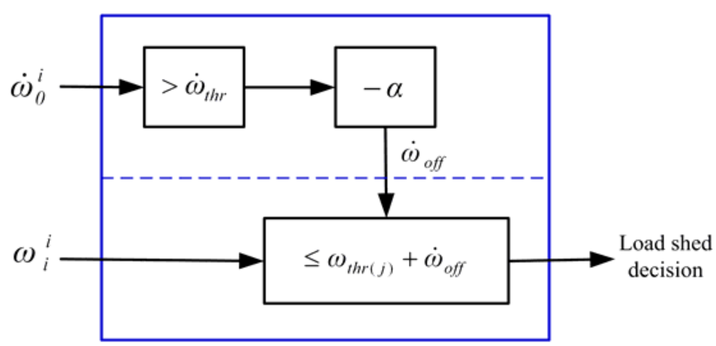


Fig. 2: The Proposed Regional Load Shedding Scheme

2. One attractive feature of the proposed scheme is a natural "robustness" to errors in $\dot{\omega}_{thr}$ threshold detection. In the event of a $\dot{\omega}_{thr}$ threshold failure, the system's worst behaviour is either the standard UFLS response or a targeted load shedding outcome and often either outcome is reasonable. In comparison, consider the poor system protection provided by fully centralized wide-area load shedding scheme during communication failure.

5. Application to a 3-region power system

5.1. Configuration of Study System

We now demonstrate our proposed load shedding scheme through simulation studies on a three region power system shown in Figure 3. Each multi-generator region is connected to other two regions. The power system parameters are given in Table 1. It is assumed that our nominal system frequency is 50 Hz and that a frequency decline below ω_{LS} = 49.75 Hz is required before any load shedding can be triggered.

The presented three region model allows the examination of regional and line overload aspects of load shedding properly. The following additional assumptions are considered:

- During nominal operation there is a 5% generation reserve in each region.
- Turbine-generator units are represented using classical 2nd order model [20] as follows. Here, K_i is a constant gain. The T_{gi} and T_{ti} are governor and turbine time constants, respectively.

$$G_i(s) = \frac{K_i}{(1 + T_{gi}s)(1 + T_{ti}s)} \tag{13}$$

- All generators have primary controllers. Further, it is assumed that there were no voltage stability issues, and that the main system dynamics are sufficiently represented by the rotor dynamics.

5.2. Design of Load Shedding Parameters

In each region, our basic load shedding thresholds were $\omega_{thr}^{0} = [49.75, 49.5, 49.25]$ Hz and the size of load shed blocks was fixed at 0.2 pu. The acceleration threshold was $\dot{\omega}_{thr} = -1$ and the bias gain was $\alpha = 0.1$.

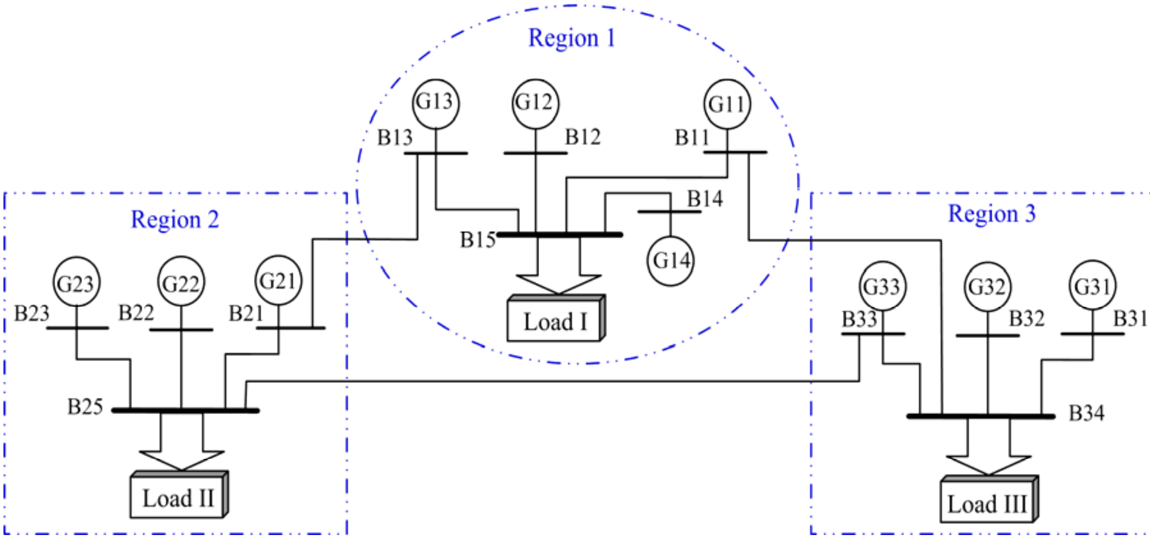


Fig. 3: Block diagram of three region system

Table 1
Applied data for simulation

Regions	*Region-1*				*Region-2*			*Region-3*		
Generator unit	G11	G12	G13	G14	G21	G22	G23	G31	G32	G33
Rating (*MW*)	1200	600	800	800	600	1200	800	1400	600	600
H_i (*sec*)	6.0	4.0	5.0	5.0	5.0	5.0	4.0	6.0	5.0	5.0
D_i (*pu MW/Hz*)	0.05	0.08	0.05	0.04	0.05	0.08	0.05	0.07	0.05	0.04
R_i (%)	3.0	3.0	3.2	2.7	2.7	2.6	2.5	2.8	3.0	3.0
T_{ti}	0.40	0.36	0.42	0.45	0.44	0.32	0.40	0.30	0.40	0.41
T_{gi}	0.30	0.20	0.07	0.10	0.30	0.20	0.15	0.15	0.15	0.20
K_i	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
T_{ij} (*pu/Hz*)	$T_{12}=0.2$ $T_{13}=0.25$				$T_{21}=0.2$ $T_{23}=0.12$			$T_{31}=0.25$ $T_{32}=0.12$		

5.3. Simulation results

For the first scenario, the system frequency response is tested following a step loss of generation 0.08 pu at 2 *s* in region 1. The frequency deviation and the corresponded frequency gradient for three regions are shown in Fig. 4. From this figure, it can be concluded that the region's frequency has not passed the first threshold frequency (49.75 Hz). Hence, emergency protection is not triggered and the steady state frequency deviation (Δf = -0.135 Hz) must be compensated by load-frequency control (LFC) loops. Since the disturbance occurred in region 1, the higher frequency rate change happens in this region. As has mentioned, the rate of frequency change is proportional to the power imbalance, but is also related to the region system inertia.

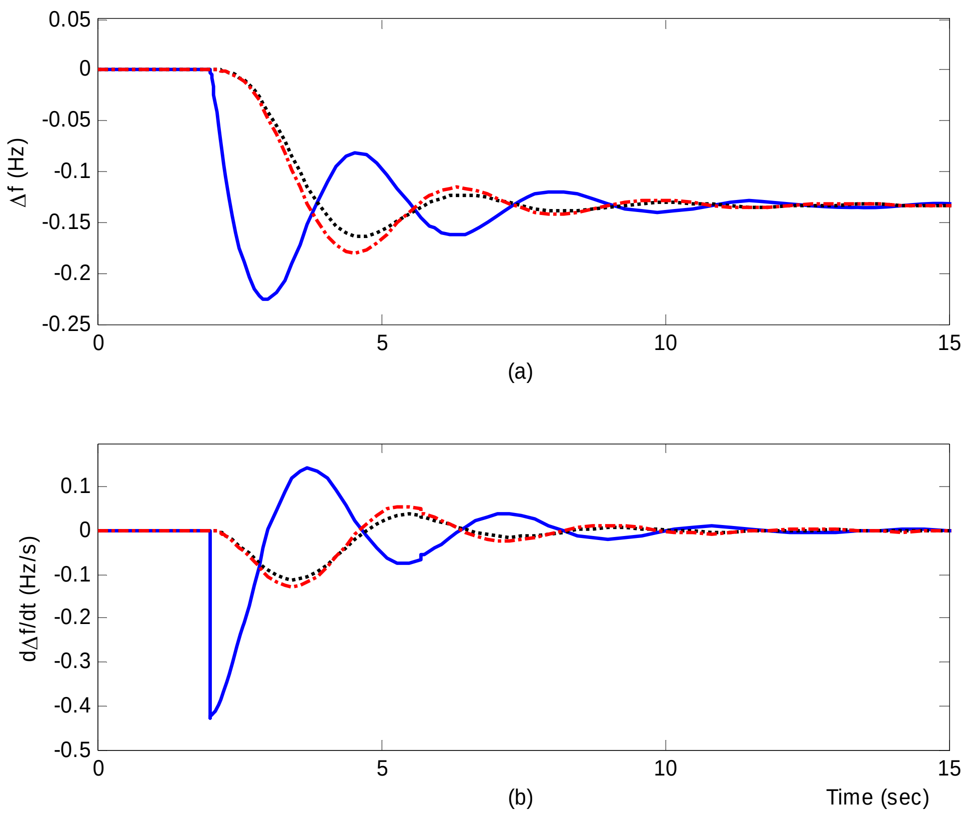


Fig. 4: System response following 0.08 pu step load change in region 1at 2s; a) frequency deviation, b) frequency gradient. Region 1 (solid), Region 2 (dotted) and Region 3 (dashed-line).

As shown in Fig. 5, the frequency changes at all generator terminals within a region are close to each others. Therefore, it is reasonable to neglect differences and assume an averaged frequency (like those shown in Fig. 4) among each region. Fig. 6 shows the total imported power change for each region following the disturbance.

For next scenario, consider the system frequency response following a 0.5 pu load step disturbance (generation loss) in region 1. Here, the total load demand is much higher than the regional power reserve, and, therefore the primary and LFC controls are not able to maintain the frequency at the nominal value. In this scenario, the system is in an emergency condition and load shedding is required to help maintain system frequency. The first load shedding event is triggered at 2.12 *s* and is quickly followed by a second required load shed event (note that load shedding actions are simulated to occur immediately after passing the relevant frequency thresholds). The system response (frequency deviation, frequency rate change and load shedding in each region) for the proposed load shedding scheme is shown in Fig. 7. Regional imported power changes in each region, following the specified major protected event, are shown in Fig. 8.

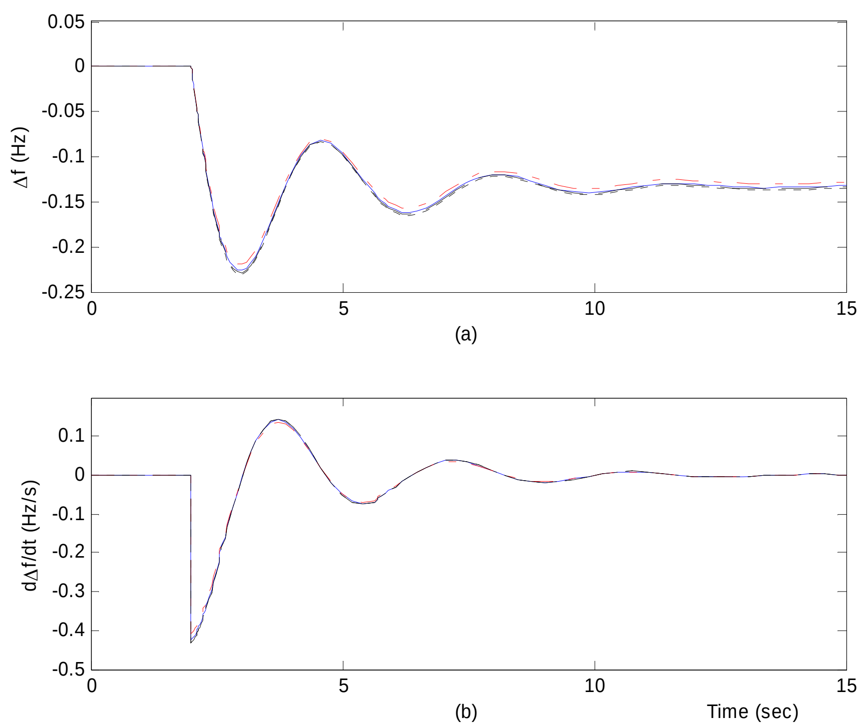


Fig. 5: Frequency response in Region 1, following 0.08 pu step load change at 2s; a) frequency deviation, b) frequency gradient. G11 (solid), G12 (dotted), G13 (dashed-line) and G14 (dotted-line).

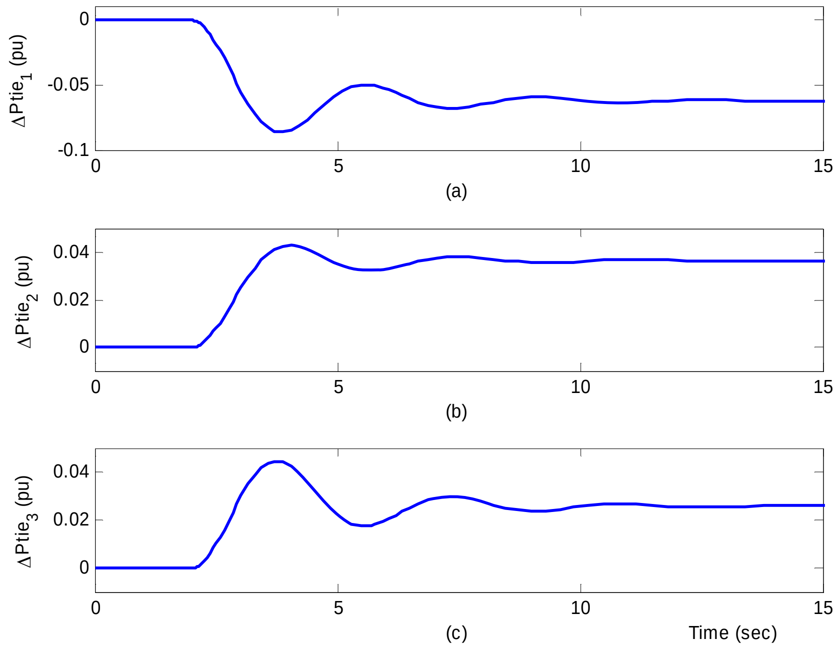


Fig. 6: Inter-region Power deviation following 0.08 pu step load change in region 1.

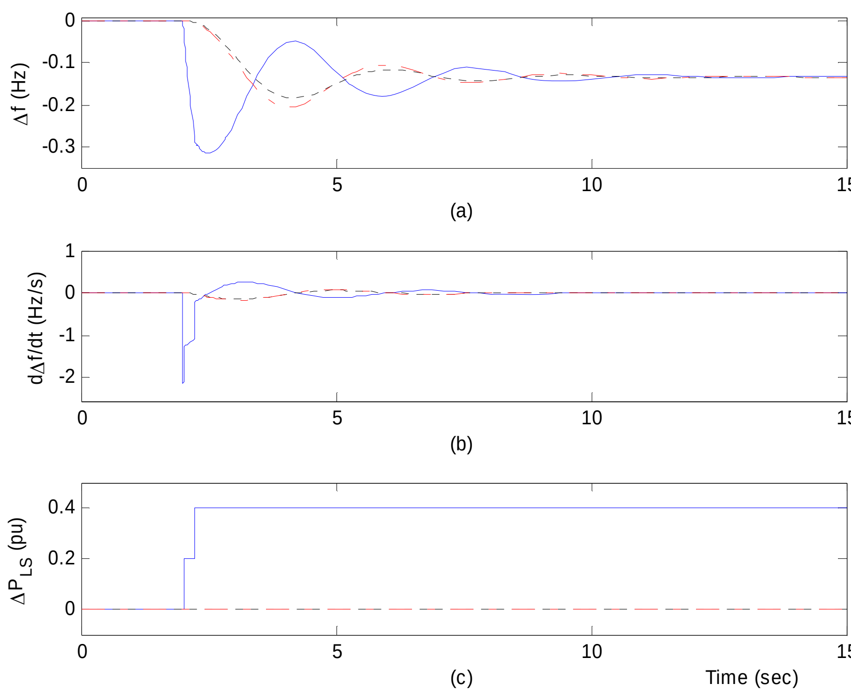


Fig. 7: System response following a major protected event; a) frequency deviation, b) frequency gradient, and c) Amount of load shedding in each region: Region 1 (solid), Region 2 (dotted) and Region 3 (dashed-line).

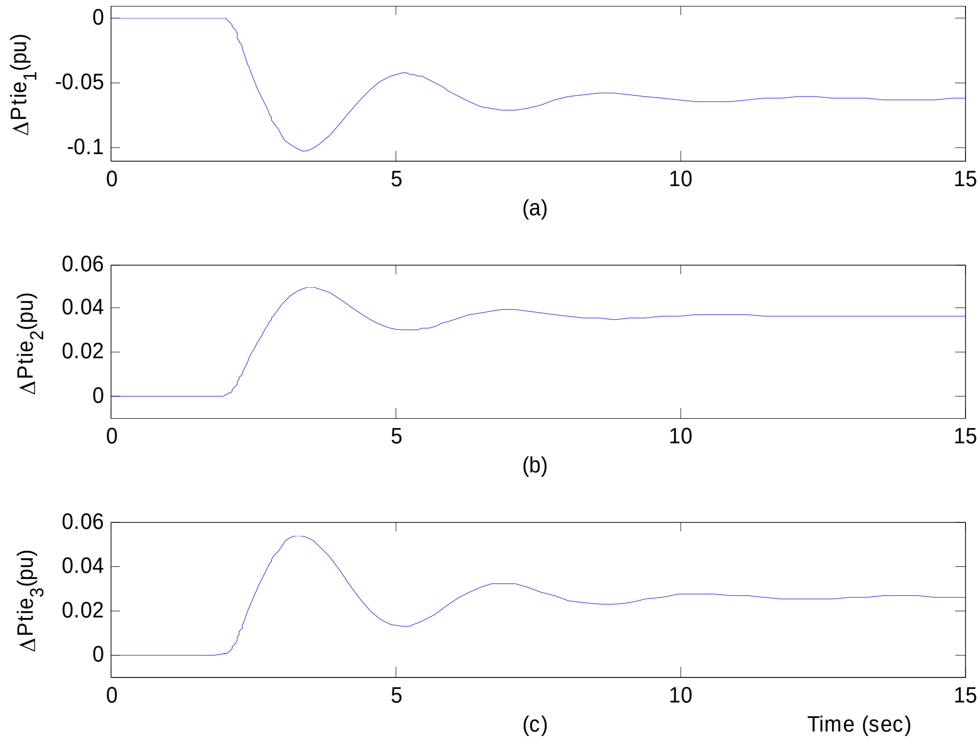


Fig. 8: Regional imported power changes.

In order to illustrate the difference between proposed (targeted) load shedding scheme and conventional (shared) load shedding schemes, the simulation was repeated and these simulation results are shown in Fig. 9 and Fig. 10.

The results shows that both shared and targeted load shedding schemes are able to stabilize the interconnected power system and stop frequency decline. However, comparison of tie-line power flows in Fig. 8 and Fig. 10 shows that to compensate the yield frequency deviation, the shared load shedding response leads to a situation with much larger inter-region power flows. As has mentioned, in certain situations these larger inter-region power flows might cause line overloading, and increase the risk of cascade failure.

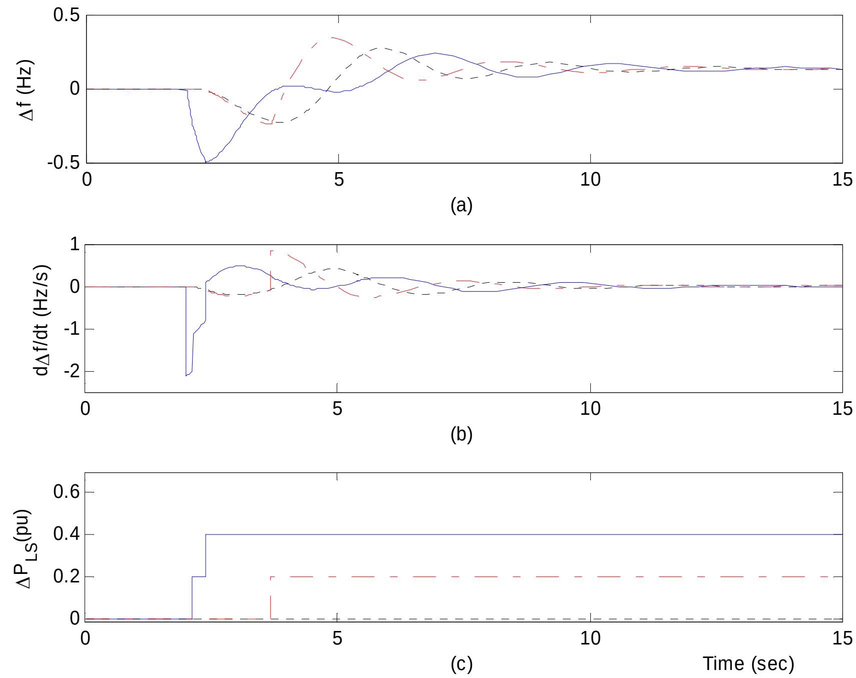


Fig. 9: System response following a major protected event for shared load-shedding scheme; a) frequency deviation, and c) Amount of load shedding in each region: Region 1 (solid), Region 2 (dotted) and Region 3 (dashed-line).

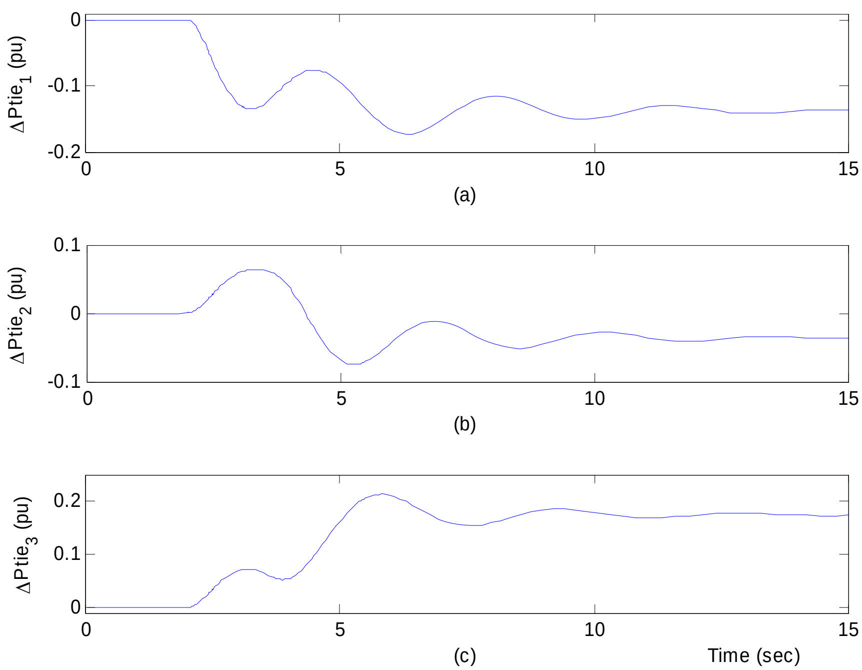


Fig. 10: Regional imported power changes for shared load-shedding scheme.

6. Conclusions

In this report, a decentralized load shedding approach is proposed. A key feature of the proposed scheme is the use of local frequency rate information to adapt the load shedding behaviour to the size and location of the experienced disturbance. Local frequency rate information is properly used to protect wide-area quantities such as inter-region power flows, and the particular manner in which we utilize frequency rate information.

The addressed method provides emergency protection not only against excess frequency decline, but also against line overloading, and hence minimizes cascade failure risks. The provided simulation studies on a three control area power system demonstrate the potential benefits of target load shedding compared to more conventional shared load shedding approaches.

Acknowledgments

This work is supported by Australian Research Council (ARC) under grant DP0559461.

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Australian Government
Australian Research Council

PROGRESS REPORT ON ARC FUNDED RESEARCH

(Discovery Projects, Large Research Grants, Research Fellowships)

Instructions

Progress reports for all Discovery Schemes are required to be submitted to the ARC by 31 January each year. Check Funding Contracts/Agreements for submission dates for earlier ARC programs but note that the ARC prefers to receive all Progress Reports by 31 January.

Researchers must note:
A Progress Report for each ARC funded research project must be completed by the **Project Leader** (generally the first-named researcher on the proposal – CI or Fellow).
The Project Leader may need to seek and enter contributions from other parties involved in the project where required (CI, PI, Fellows, Partner Organisations).
While there is no limit to the textual information that can be provided, the ARC is generally seeking 1 to 2 paragraphs of information where a textual response is required.
Once complete**,** the Project Leader (CI or Fellow) should submit the **signed paper copy** of the Progress Report to the Research Office of the Administering Organisation. The signed copy must include other signatures where required.
The completed Progress Report should be saved as a rich text format (RTF) or scanned (PDF) document. The file name for the Progress Report should conform to the following naming convention: **[ProjectID][CI1Surname].rtf**
(For example DP0312345Brown.rtf)
The saved RTF or PDF file should be attached to an **email** and sent to the Research Office of the Administering Organisation.

Research Administrators must note:
Progress Reports should be submitted to the ARC in **paper and electronic (RTF orPDF) format.**
The paper copy (signed by the Deputy Vice-Chancellor (Research) or equivalent) must be sent to:
Progress Reports
Australian Research Council
GPO B ox 2702
Canberra ACT 2601
The electronic copy (RTF or PDF) must be emailed to the ARC at progress.reports@arc.gov.au.
Please ensure the file name for the electronic version conforms to the naming convention detailed above (files inappropriately named will be returned to the Research Office for action).
Financial reporting in this Progress Report should be consistent with the advised financial details to be provided in the relevant End of Year Report (due for submission by 31 March).

PROGRESS REPORT ON ARC FUNDED RESEARCH

FOR DISCOVERY PROJECT ACTIVITIES IN THE YEARS 2007-2008

1. PROJECT IDENTIFICATION

1.1 Program

Discovery Project

(select Discovery Projects; Large Research Grants; Research Fellowships)

1.2 Project ID

DP0559461

1.3 Current Administering Organisation

Queensland University of Technology

If this project was transferred during this reporting period, please indicate the name of the relinquishing Administering Organisation and date of ARC approval:

____

___/___/___

1.4 Total amount of ARC funding received for this reporting period

$

1.5 Project title

Power Systems Emergency Control

1.6 Project Leaders

Name	Gerard Ledwich, Arindam Ghosh
Role (CI or Fellow)	CI
Email address	g.ledwich@qut.edu.au, a.ghosh@qut.edu.au
Work phone number	07 3134 2864
Mobile phone number	

If the current Project Leader is not the same name as the original Project Leader on the Proposal, please advise below the name of the original Project Leader and the date of ARC approval for the change in Project Leader:

Original name __________________________ Date approved by ARC

___/___/___

1.7 CIs, PIs, Fellows

List all CIs, PIs, Fellows that have been named in the Proposal or Project and their current status. If they were not in the original Proposal or have been withdrawn from the Project please provide a date that the change (addition or withdrawal) was approved by the ARC.

Researcher Name and Organisation	Researcher role (CI/PI/APD)	**Researcher Status** (eg: Original, Additional or Withdrawn)	**ARC Approval Date** (for Additional and/or Withdrawn only)
H Bevrani, QUT	Senior Research Fellow	Origina	
J J Ford, QUT	CI	Original	
ZY Dong, The University of Queensland	CI	Original	

2. *PROJECT DESCRIPTION AND OBJECTIVES*

2.1 100 word Project summary [as indicated in the original proposal]

Major Power system blackouts are a low probability high impact event. The present responses from power system operators are able to avoid most predictable events. When more unexpected events occur the best response and the appropriate level need to be determined quickly. The integration of new tools for dynamic control and automated processes for emergency control offer a unique opportunity to reduce vulnerability and to limit the potential for one failure to trigger another.

This project appraises the network points which are most stressed and determines the combination to relieve that stress without and excessive impact on customers.

2.2 Summary of original objectives of project

This project aims to develop dynamic and emergency control techniques to enhance interconnected power system stability. A power system is a complex system with numerous components and rich dynamics. With the deregulation of the power industry worldwide, the power systems are being stressed toward their stability limits in many countries. The recent North America blackout in Aug 2003 and Italy in Sept 2003 set an alarm for power system stability and reliability for all other major electricity grids elsewhere including Australia.

The Australia power grid is one of the largest in geographical scale however in general it has weak links connecting different regions of: New South Wales, Queensland, Victoria, Snowy regions, South Australia and Tasmania. This project investigates one of the most important properties of the power industry, system stability and retention of synchronism, making use of advanced techniques. The outcome of this project will provide an integrated framework for developing dynamic and emergency controls to maximize retention of synchronism and to address the issues which lead to the development of cascade failures and system blackouts.

Contingency control in a power system requires reliable and effective control activities to maintain the system stability under unexpected system disturbances such as lost of generation or transmission lines. This refers to the requirement to operate such that no loss of supply should occur for any single credible event (contingency). In the National Electricity Market (NEM) of Australia, the required contingency control time line is 20 minutes to identify the instability problem and within another 10 minutes to activate the control and bring the system into a stable operational condition [26]. When multiple contingencies occur in a short time then special responses need to be triggered.

In this proposal, the investigators are to explore potential for improvement in contingency analysis and emergency control which are emerging from merging tools such as on-line load modelling, predictive control and cutset analysis.

3. PROJECT OVER DURATION OF FUNDING

The information you provide in this section is confidential and will not be used for media or promotion of research.

3.1 Have there been changes to the project? yes (yes/no)

This could include changes to the research project resulting from ARC funding at a lower level than requested. Note that some changes require ARC approval to be requested as a Variation to the Funding Contract/Agreement. Such a variation must be forwarded to the ARC through the Administering Organisation's Research Office. Forms requesting Variations to Funding Contract/ Agreement are available on the ARC website at www.arc.gov.au.

By indicating changes to the budget, aims and research plan in this Report, you are requesting ARC approval for a revision of the Project. A 'satisfactory' assessment of the Report and the Project means that the revision has been approved.

If yes, give details

Arc funding lower than request. Under the original plan there were to be two PhD students, one at each university. The scope reduction is small but some of the validation of concepts has been slower with the reduced number of students and the delayed start of the one student.

3.2 What were your research plans and objectives for the period covered by this Report?

(The answer to this question should be consistent with the original Proposal or the preceding Progress Report.)

The project plan was to develop appropriate analysis/synthesis techniques on power system emergency control issue.

3.3 Did the research project proceed as planned? What have you achieved over this period? Outline the research findings to date.

The research project has proceed as planned and during this year, progress was made in five distinct areas:

1. Modified the conventional low-order power system frequency response model and develop an analytic approach to analysis the system behaviour in off-normal and emergency conditions.

2. Develop a robust model predictive control technique to first swing stability protection to first swing stability protection of vulnerable power system transmission lines.
3. Improved transient stability against large disturbance faults using new control techniques.
4. Develop analysis methodologies to study power system modes and transient stability.
5. One postgraduate student has completed his thesis and a number of quality publications have been generated under this project.

3.4 What are your research plans and objectives, including publication plans for the coming year?

(Please note that in your next Report, you may be asked to report progress against these plans and objectives.)

- Extend the research project to develop more effective and comprehensive analysis/synthesis scenarios for power system emergency control issue.
- Study on feasibility of regional frequency-based emergency control schemes.
- Examine the proposed methods/algorithms for large scale power systems, using more real models and appropriate software(s).

4. FELLOWS ON TEAM PROJECTS

(Discovery-Projects, Research Fellowships)

This section needs to be completed by each ARC Fellow on the project unless the Fellow is the sole researcher on the project. If there is more than one Fellow associated with the project, each Fellow must respond. The Fellowship section may be deleted if not relevant.

Name	Hassan Bevrani
Fellowship Type (APD, ARF, QEII, SRF, APF)	
Describe your contribution to the Project	I am working full time on the project to conduct research work on the specified scopes.
Describe how the research environment (including facilities and support, as well as the intellectual environment) is supportive of your Fellowship?	The research environment is acceptable and the host university and the project leader are trying to provide necessary facilities and supports.
Comment on other aspects of the research environment, if appropriate	I am working full time on the project to conduct research work in the specified scopes.

4.1 Fellow 1

(Note: If there is more than one Fellow on this project, replicate Section 4.1 for each additional Fellow)

(THE FOLLOWING CERTIFICATION RELATES ONLY TO PROJECTS INVOLVING APDs

8.3 Certification by Academic Supervisor or head of AOU

Australian Postdoctoral Fellowships (APD)

Reports on postdoctoral fellowships require the signature of the academic supervisor or head of the academic organisational unit (AOU) (department, school, faculty).

Academic supervisor or head of AOU-comments

I certify that progress has been satisfactory and/or problems have been identified in this Progress Report, and I recommend continued funding:

Supervisor/head of AOU

Signature ____________________________ Date ___/___/___

Thank you for submitting your Progress Report.

The ARC may contact you if clarification or further information is required to determine whether progress has been satisfactory over the period covered in the Report.

Information on this form is collected in order to determine whether the research project funded by the ARC has reached satisfactory completion and for post award reporting.

Researchers should note that if the ARC is not satisfied with the progress of the Project, further payment of funds will not be made until satisfactory progress has been made on the Project. If satisfactory progress is still not achieved, the Funding will be terminated and all outstanding monies recovered by the ARC. Unsatisfactory progress on the Project will be noted against any further proposals under any ARC scheme submitted by, or on behalf of, the Chief Investigator or Fellow and will be taken into account in the assessment of those proposals.