AN OPTIMAL DYNAMIC UNDERFREQUENCY LOAD SHEDDING SCHEME

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To my beloved mother, brothers, sisters, wife and children

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ABSTRACT

Electric power system network is highly sensitive to the supply and demand of power at generation as well as at user level. Erratic power demand under prevailing generation conditions may cause decay in power system frequency that can lead power system network towards cascading, islanding or blackouts. To avoid this undesirable situation and further streamline the system, load shedding is one of the safe alternative to restore the frequency from further decay. Numerous researches have been conducted on this aspect of the problem; however, there is a potential for another provision through optimization of the load shedding. Therefore, the main purpose of this project is to devise and present an optimal dynamic underfrequency load shedding scheme. The parameters studied in this study include: the implementation of developed dynamic underfrequency load shedding relay, the modified and simplified primary controllers (turbine governor and automatic voltage regulator) and the application of dynamic loads (especially frequency dependent loads) to enhance the load shedding optimization using power system simulation tool. The developed algorithm for underfrequency load shedding relay has considered load priority whereby the load with least priority will be shed first. The algorithm has been tested on some IEEE standard systems and one utility system. These test systems include the IEEE 9, 39 bus systems and one 27 bus utility system. The results of these test cases confirm the achievement of the objectives of this thesis such as; saving of load shedding amount of 1 MW, 2 MW and 0.01 MW in IEEE 9, 39 bus systems and 27 bus utility system respectively. Other achievement includes reduction in load shedding steps i.e. for each test case, the complete load shedding was achieved in 3 steps compared to 4 or more steps in other researches and the frequency converged to its nominal value in less time i.e. 3 sec, 5 sec and 10 sec in each test case respectively, compared to greater than or equal to 20 seconds in other researches.

ABSTRAK

Sistem rangkaian tenaga elektrik sangat sensitif terhadap penghantaran dan permintaan kuasa samada pada tahap penjanaan serta penggunaan. Permintaan kuasa yang tidak menentu pada sistem penjanakuasa boleh menyebabkan pengurangan atau kejatuhan nilai frekuensi pada sistem rangkaian sehingga boleh berlakunya berturutan, masalah kepulauan atau bekalan elektrik terputus. Bagi mengelakkan daripada situasi yang tidak diingini dan untuk lebih mengefektifkan sistem, penyahbebanan adalah salah satu penyelesaian yang boleh digunakan untuk memulihkan sistem daripada kejatuhan nilai frekuensi yang lebih teruk. Banyak kajian telah dilakukan pada aspek permasalahan ini, namun terdapat kaedah lain iaitu melalui pengoptimalisasian penyahbebanan pada sistem boleh dilakukan. Tujuan utama projek ini adalah untuk memperkenalkan skim yang optimum mengenai penyahbebanan sekiranya sistem berada di bawah paras frekuensi. Parameter yang digunakan dalam kajian ini termasuklah penggunaan geganti bagi penyahbebanan dibawah paras frekuensi, pengubahsuaian dan permudahan kawalan utama (pengawalimbang turbin dan pengatur voltan automatik) serta penggunaan beban secara dinamik (terutamanya bagi beban yang bergantung pada frekuensi) untuk meningkatkan pengoptimuman penyahbebanan dengan menggunakan kaedah simulasi sistem kuasa. Algoritma yang dibangunkan untuk geganti penyahbebanan di bawah paras frekuensi ini telah mengambil kira faktor keutamaan beban di mana beban yang mempunyai keutamaan paling rendah terlebih dahulu dinyahbebankan. Algoritma ini telah diuji pada beberapa sistem IEEE yang piawai dan satu sistem utiliti. Sistem yang diuji ini meliputi sistem IEEE 9, 39-bas dan satu utiliti sistem 27-bas. Keputusan dari ujikaji menunjukkan pencapaian objektif tesis ini seperti penjimatan penyahbebanan sebanyak 1 MW, 2 MW dan 0.01 MW pada sistem IEEE 9, 39-bas dan sistem utiliti 27-bas. Pencapaian lain termasuklah pengurangan langkah pada penyahbebanan dimana untuk setiap kes ujikaji, penyahbebanan yang lengkap dapat dicapai dengan hanya 3 langkah berbanding 4 langkah atau lebih yang dilakukan oleh pengkaji yang lain dan tempoh bagi frekuensi untuk kembali pada paras nominal adalah kurang iaitu 3 saat, 5 saat dan 10 saat untuk setiap kes tersebut berbanding dengan 20 saat atau lebih untuk tempoh yang dilakukan sebelum ini oleh pengkaji yang lain.

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Variable in DSPF		**Variable Name in DSPF**
δ_e	-	Electrical Power Angle
ϑ	-	Phase or voltage angle
ω_0	-	Synchronous Speed or Nominal Angular Speed
$\leq$	-	Less than or Equal to
$\frac{1}{2}mv^2$	-	Kinetic Energy
C	-	Capacitance
d	-	Deviation of or Change in referred parameter from its nominal
d/dt	-	Rate of change of
df_edt or $ROCOF$	-	Derivative of Electrical Frequency or ROCOF
df_ehz or df_e	-	Deviation of Electrical Frequency
df_eq	-	Deviation in Quasi Frequency
df_{rot}	-	Rotor angle deviation
$dfrotx$	-	Maximum deviation between δ between the synchronous machines in the system
$dload$	-	Change in Load
$dltbr$	-	Breaker Operating Time
$dltfr$	-	Time Delay
$dorhz$	-	Speed deviation
$dpgt$	-	Deviation in Electrical Power Generated

dP_{load}	-	change in P of Composite Load
dP_{load0}	-	change in P of Composite Load in f_e Independent component
dP_{loadf}	-	change in P of Composite Load in f_e Dependent component
dP_T	-	Deviation in Mechanical Turbine Power input to Generator
$droop$	-	Frequency Droop
$f_e(0)$	-	Initial f_e
$f_e(\infty)$	-	Final f_e
$f_e hz / f_e$	-	Electrical Frequency in Hz/p.u.
$f_e q$	-	Quasi-frequency
$f_{\min}$	-	Minimum allowable/settling Frequency
fr_{dev}	-	Average frequency
f_{rnom} or f_{set}	-	Nominal frequency or Set Frequency
fr_{ref}	-	Reference Frequency
h / hpn	-	Inertia based on MVA or MW
I_0	-	Current
K	-	Secondary f_e bias/gain
k	-	Constant of Proportionality
Kpf	-	Primary f_e bias/gain
kpf	-	Load reduction factor or damping constant
L	-	Inductance
$loading$	-	Overload/ Overloading
$loading_0$	-	Initial loading
P	-	Active or Real Power
P_{gen}	-	Active Power Generated
P_{gen_sum}	-	Total Active Power of Generation
pgt	-	Electrical Power Generated by Generator
phi	-	Rotor angle of the q-axis with reference to the reference U of the network (=firot-90°)
P_{load}	-	Active Power of Load

P_{load_sum}	-	Total Active Power of Load
$P_{load\_sum\_c}$	-	Total Active Power of the Loads Connected
P_{loss}	-	Total Active Power loss
P_{loss}	-	Active Power Loss
$P_{\max}$	-	Power Transfer Capability
P_T	-	Mechanical Turbine Power input to Generator
p_z	-	Generator number of pair of poles
Q	-	Reactive Power
R	-	Resistance
S_{base}	-	Base Apparent Power
S_{gen}	-	Generator Nominal Apparent Power
$Shed_{load}$	-	Total load which must be shed
$\sin \delta_e$	-	Amplitude of Power Angle
S_{nom}	-	Power rating
T_a	-	Accelerating torque
T_{gen}	-	Generator torque
T_{load}	-	Load torque
T_s	-	Relay Operating/Pickup Time
U or u	-	Voltage or voltage magnitude
W_k	-	K.E. of the rotating masses
xme	-	Electrical or Generator Torque
xmt	-	Mechanical or Turbine Torque
$xspeed$	-	Speed of Generators
Y	-	Admittance
Z	-	Impedance

LIST OF ABBREVIATIONS

+ve	-	Positive
AGC	-	Generation Control or Automatic Generation Control
AI	-	Artificial Intelligence
AS	-	Slip Iteration
ATE	-	Area Transient Error
av	-	average
AVR	-	Automatic Voltage Regulator/Exciter
CIGRE	-	International Council on Large Electric Systems
CSC	-	China Steel Corporation
DE	-	Differential Equations
DS	-	*DIgSILENT*
DSL	-	DIgSILENT Simulation Language
DSPF	-	*DIgSILENT PowerFactory* 14
DUFR	-	Discrete UFR
EMT	-	Electromagnetic Transient
ETMSP	-	Extended Transient-Midterm Stability Package
Exe	-	Execute
FD	-	Frequency Domain
FSM	-	Finite-State Machines
FTR	-	Frequency Trend Relay
GA	-	Genetic Algorithm
GEC	-	General Electric Company
GOV	-	Governor
GPA	-	Guam Power Authority

IASTED	-	International Association of Science and Technology for Development
IC	-	Initial Condition
IEEE	-	Institute of Electrical and Electronics Engineers
K.E.	-	Kinetic Energy
km	-	kilo meter
LC	-	Load Curtailed/Load Curtailment
LDS	-	Total load which must be shed in p.u.
LDS		
LF	-	Load Flow
LFA	-	Load Flow Analysis or Power Flow Analysis
LFC or ALFC	-	Load Frequency Control or Automatic Load Frequency Control
LPF	-	Low-pass Filter
LS	-	Load Shedding
LSEOL	-	LS equal to OL
LSEOL		
LSR	-	Load Shedding Relay
LSS	-	Load Shedding Scheme
mmf	-	Magnetomotive force
msec	-	milli second
Mvar	-	mega var
MW	-	mega Watt
mW	-	milli Watt
NAERO	-	North American Electric Reliability Organization
NERC	-	North American Electric Reliability Council
NN	-	Neural Net
NR	-	Newton-Raphson
OC	-	Open Circuit
OF	-	Over-frequency
OL	-	Loading or Overloading
OS	-	Over shedding
p.u.	-	Per Unit

PDSS	-	Power Distribution System Simulator
PES	-	Power and Energy Society
PF	-	Power Flow
PF14	-	*PowerFactory 14*
PFUM	-	*PowerFactory* 14 User Manual
PS	-	Power System or System
PSA	-	Power System Analysis
PSS	-	Power System Stabilizer
RAS	-	Remedial Action Schemes
RMS	-	Electromechanical transient
SC	-	Short Circuit
SCADA	-	Supervisory Control Centre Department
sec	-	Seconds
SL	-	Slack
SPS	-	Special Protection Schemes
SYM	-	Synchronous Machine
TC	-	Time Constants
TD	-	Time Domain
TDS	-	Time Domain Analysis/Simulation
TG	-	Turbine Governor
TNB	-	Tenaga Nasional Berhad
UF	-	Underfrequency
UFLS	-	Underfrequency Load Shedding
UFLSR	-	Underfrequency Load Shedding Relay
UFLSS	-	Underfrequency Load Shedding Scheme
UFR	-	Underfrequency Relay
US	-	Under shedding
UV	-	Under Voltage
-ve	-	Negative
VT	-	Voltage Transformer
WCC	-	Western Coordination Council
WSCC/ WECC	-	Western Electricity Coordination Council

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CHAPTER 1

INTRODUCTION

1.1 Background

In a stable and balanced power system (PS) network, all generating power stations are tied together and interconnected at constant power frequency or nominal frequency (f_{rnom}) but at different transmission voltage (U) levels. This is to feed the loads at different destinations in a radial or ring main way. The load demand, and need of more comfortable and luxurious life has given PS a new shape in day to day topology and stability limits. One of the examples at transmission end is wider PS network starting from medium transmission U to extra even ultra high U levels and increase of power electronics devices at the utilization end.

The geographical infrastructure of PS is directly related to climate and topographical structure of the area since it varies from very hot to cold even icy, humid to dry weather, open areas to congested areas, hilly areas to planes, and tropical to sub-tropical seasons. In this wider structure of PS, expected or unexpected natural calamities, some human errors are unavoidable to affect PS transmission network and in turn causing unbalance between supply and demand affecting its f_{rnom}. The use of power electronic appliances at consumer end also adds

f_{rnom} an oscillating nature, while improving load shedding scheme (LSS) at optimal value needs more concentration in the area of PS stability and control.

The complex nature of modern PS (i.e. consisting of few hundreds of buses to thousands of buses with tens of generators to hundreds of generators respectively) leads to breakdowns, islanding, or blackouts either due to normal switching of bulk loads, natural cause, malfunction of protecting devices, human error or difference between generation and supply demand, i.e. due to increase in load demand.

At the planning level to overcome these untoward incidents (which on one hand suffers an enormous economical loss and on the other hand loss of trust of the consumer), design of some optimal LSSs including primary controllers like Turbine Governor (TG) or Governor (GOV), Exciter or Automatic Voltage Regulator (AVR), and Stabilizers or Power System Stabilizer (PSS) design or modifications are needed to bring back the f_{rnom} to its near possible value and/or to meet the objectives in the transient period like generator outage, sudden bulk load change or switching of the load, line fault and its tripping etc.

Complexity of PS stability has been a challenging issue for PS engineers since its recognition in 1920, when it was firstly observed as an important problem. Results of the first laboratory tests on miniature systems were reported in 1924; the first field tests on the stability on a practical PSs were conducted in 1925 (Proteus, 1920; AIEE Subcommittee Report, 1937; Prabha *et al.*, 1994; Prabha *et al.*, 2004).

Gregory (1991) has reported that until mid-1960s there was no major issue of reliability (i.e. the probability of satisfactory operation of PS for long and planned time, or the ability of PS to supply continuously satisfactorily, with few interruptions during the period) of bulk electric supply, either within electric utility industry or within its various publics. But this was realized by about 30 million people as their dependency on electricity when, on Tuesday November 9, 1965 at 5:16p.m., the nation experienced a biggest power failure in history across the Northeastern US and Ontario, Canada (Bishop, 1999), which lasted for 13 hours, while major power outages happened before and after this unique occasion but not severe of same situation.

Robustness of a system is defined by its ability to maintain stable operation under normal and perturbed conditions (PowerFactory, 2010). The PS can go under various conditions i.e. Normal, Stable-Alert, Preventive-Emergency, Immediate-In-extremis, Heroic and Restorative or Corrective (Lester and Kjell, 1978; Prabha, 1994) as shown in Figure 1.1.

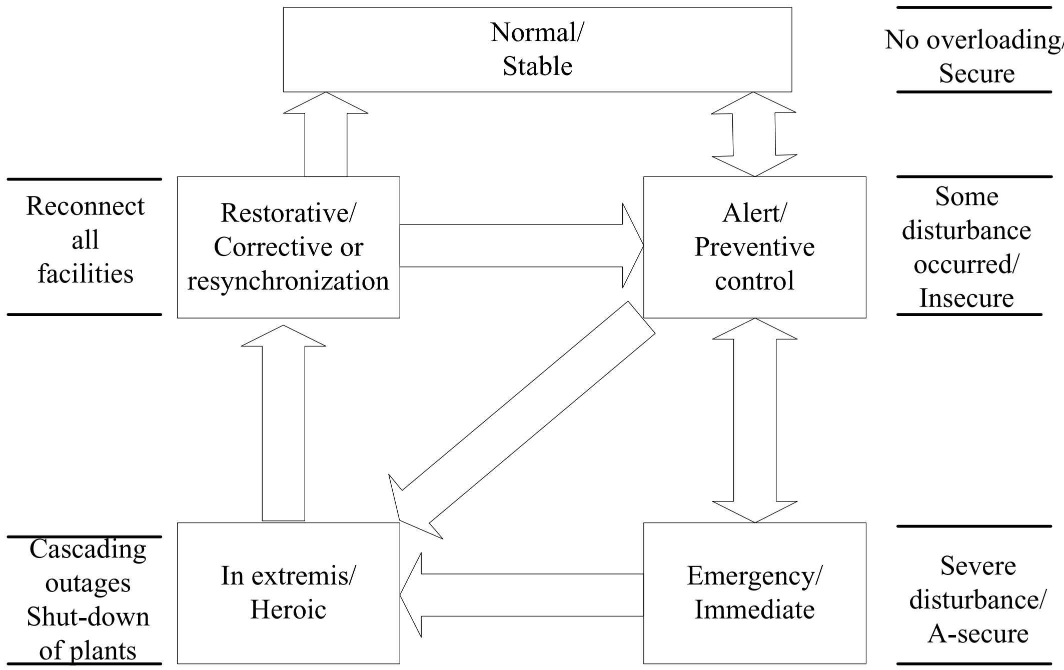

Figure 1.1 Power System Operating States

The question of level of security (i.e. limits applied against any disturbance caused at PS such as short circuits) as a control (online or offline) and robustness of a PS was discussed when in US a blackout (as of the first category) due to frequency (f_e) sag which remained for 7 hours in January 1977 and again on July 13, 1977 when thunderstorm and lightning was struck on two 345 kV transmission lines causing their tripping (Lester and Kjell, 1978).

Two blackouts due to fault at China Steel Corporation (CSC) and a ground fault at neighboring industrial customer (in December 1992) served by the same substation affected a serious blackout in CSC (Yenn *et al.*, 1996). Similar problem was also reported in western and northern India grid stations in 1995 to 1997 (Chandekar and Tarnekar, 2002). Likewise, on July 29, 1999 Tai power system in (Taiwan) had also received significant loss of energy for a long period due to failure of the 345 kV transmission line (Yi *et al.*, 2005).

The reports also show that similar problems (supply interruptions resulting in cascaded tripping), over the world, of power failure also occurred during 2003. Such type of interruptions, which are known as the worst PS failures in last few decades especially just in two months i.e. August and September 2003 are as under:

i) *US-Canada blackout of August 14, 2003*: Many states of North America were affected and went in dark due to power interruption/failure of North American Eastern Interconnection of 63 GW load (Amin, 2004; Andersson *et al.*, 2004a; 2005b; Yuri *et al.*, 2005).

ii) *August 28, 2003 Central UK blackout*: August 28, 2003 at 1826 hours, Central UK (Amin, 2004; Yuri *et al.*, 2005; Andersson *et al.*, 2005) faced a catastrophic failure caused by a fault in the 275 kV national grid system affecting a ring around London affecting at least 250,000 people.

iii) *Grand Northern Malaysia blackout in 2003*: September 01, 2003 at 0958 hours, Northern Malaysia (TNB, 2003).

iv) *September 23, 2003 blackout in Southern Sweden and Eastern Denmark*: September 23, 2003 at 1235 hours, nearly four million (1.6 million people in Sweden and 2.4 million people in Denmark) customers lost total load power of 4700 MW in Southern Sweden and 1850 MW of load in Eastern Denmark following a cascading outage that struck Scandinavia in 2003 (Amin, 2004; Andersson *et al.*, 2004a; 2005b; Yuri *et al.*, 2005).

v) *Italian blackout of September 28, 2003*: On September 28, 2003 at 0328 hours many parts of Italy and Southern Switzerland remained in dark due tripping of major tie-line supplying to Switzerland and other countries of Western Europe in last quarter of the 2003, and Southern Switzerland (Sandro and Carlo, 2004; Andersson *et al.*, 2004). Such disaster was also experienced in Karachi Pakistan, on July 29, 2006, where almost half of the Karachi city (industrial and biggest city) including one of the largest Steel Mill of Asia experienced a major breakdown due to supply suspension from National Grid affecting 21 out of 52 Grid stations. The power was restored after 12 minutes (http://dawn.com.pk/2006/07/30/local4.htm, 2006). In addition, other countries such as; Singapore, Brazil, UK, USA, Indonesia, Italy, China, Denmark, Sweden, Switzerland, Canada, Iran, Australia, Thailand, Malaysia, Taiwan, also had major blackouts at different timings of the year under report (Majid and Mohammad, 2004; Andersson *et al.*, 2004; CIGRE Working Group B5.21, 2005).

Due to blackouts, these countries have suffered a big economic loss (millions of dollars) and losing of trust of the consumer. One of the causes of blackout is due to underfrequency (UF) constraint. Some of the causes of UF are: severe demand and generation gap or imbalance, protection system failures, incorrect or slow actions of system operator. Generally, UF causing power interruptions are due to stresses produced on the generators exceeding its limits causing them to trip. The difficulty in seeking solutions is to prevent cascaded tripping from a single outage that eventually leads to violations of *n-1* contingencies. An important fact is that, such electrical problems will continue to happen and cannot be completely prevented. Causes of these outages can be due to lightning strikes, storms, broken conductors, random equipment damages, terrorist firings on towers or lines and/or transformers, fire, tree encroachments or human errors.

One of the factors that often delay the restoration process is either loss of generation or tie line tripping or overloading ($loading$) when load exceeds the generation, it could disturb the balance between generation and demand causing f_e decline. This f_e decline due to mismatch of generation to meet the demand will acquire power from the stored energy from prime mover and will slow down the rotation or speed (in turn reduction in f_{rnom}).

However, if the disturbance is not severe, the reservoir will have tendency to compensate it, otherwise if this loss is not corrected in the predetermined time the f_e will decline rapidly and will affect the main components of steam plant i.e. station auxiliaries, the turbine and thus reducing cooling and efficiency of the system leading it to trip or shut down the plant through protection devices. Other PS accessories affected by abnormal f_e include generator and the step-up transformer (Rockefeller *et al*., 1988; PS Relaying Committee, R2009).

After contingency, the system is in dynamic phase leading to long or short term f_{rnom} instability which is determined by; inertia (h or hpn, rated to MVA or MW respectively), and $loading$ capacity of the generators. Through these parameters, the in-equilibrium condition of the generation and load can be predicted directly after the disturbance occurred. In this case, some immediate and pre-selected LSS can provide a path for the PS to restore the f_{rnom} back to its **set value**. The UF needs to control the governor runback or count operator action to correct the turbine speed.

The convergence problem, has been found in the form of overshoot and/or undershoot of the f_e due to over shedding (OS) and/or under shedding (US) of the load respectively (Mahmoud *et al*., 1995; Abdullah *et al*., 2004). This may be either due to lack of coordination between load shedding (LS) steps and the corresponding f_e, delay between the steps, or effect of some system equipments (i.e. f_e dependent loads). Hence to acquire optimal underfrequency load shedding scheme (UFLSS), beside other parameters affecting f_{rnom}, capacitor banks; f_e dependent loads; etc. are some of the variables which are needed to be studied.

The invention of underfrequency relay (UFR) from its time taking electromechanical to very fast acting numerical ones nowadays it is possible to detect the incident and take fast action against cause through underfrequency load shedding relay (UFLSR). Various LSSs from its traditional to automatic even dynamic UFLSSs have been reported by different researchers. In different countries the stages used for UFLSSs are found to be from 5 to as many as 15. The fast action of these numerical relays can be utilized in order to enhance their work and hence with the proper programming of numerical UFLSRs optimal results are possible.

However, in order to overcome such type of incidences; PS experts around the world were/are called and discussions were/are made also. PS Stability as well as PS Stability Controls Subcommittees of the Institute of Electrical and Electronics Engineers (IEEE) Power & Energy Society (PES), Western Electric Coordinating Council (WECC), PS Dynamic Performance Committee meetings were/are invited, and at various International forums such as: International Council on Large Electric Systems (CIGRE), IEEE, North American Electric Reliability Corporation (NERC), International Association of Science and Technology for Development (IASTED), North American Electric Reliability Organization (NAERO) etc. were/are held to sort out the problem and recommend ways and means to get rid of these incidences or to reduce the risk of major blackouts by using emerging technologies in future.

1.2 Power System Stability, Control and Blackouts

Reflecting the current industry needs, definition of PS Stability is required to be redefined with reference to the experiences, and understanding, which is physically motivated similar to any dynamic system (confirming to precise mathematical definitions) providing systematic basis for its classification, reliability and security. One of the definitions of PS Stability as given by Prabha *et al*. (2004) depicts that an electric PS should be able to regain the state of operating equilibrium duly coupled with whole system after exposed to a physical disturbance at initial operating condition.

The classification of PS stability (Prabha *et al*., 1994; Prabha *et al*., 2004) is shown in Figure 1.2. Due to dynamic behavior of PS broadly, it can be divided into different dynamic phenomena (Jan *et al.*, 1997) as shown in Figure 1.3. Further, dynamic phenomena can be separated into different transient areas of study i.e. short-term transients (or electromagnetic transients), mid-term transients (electromechanical transients), long-term transients according to their time scale characteristics and f_e bands (Prabha *et al*., 1994; PowerFactory, 2010) as shown in Figure 1.4.

Since rotor angle (phi) and f_e stability falls in the scope of this research hence it is discussed here. On the basis of general definition of PS stability, two categories of stability are derived; small-signal and large-signal stability with nonlinear dynamics. Under small-signal stability the system will return back to the normal operation with a small disturbance; and this may be worked out through linearized state space equation to delineate the PS dynamics. Whereas, the large or transient stability of the system brings system back to its normal state, but with a high disturbance to the extent of loss of the circuits (single/multi phase) and even to generation unit. Under these circumstances linearized PS model will not apply, thus the use of nonlinear equations for analysis would be useful for direct analysis of the PS dynamics.

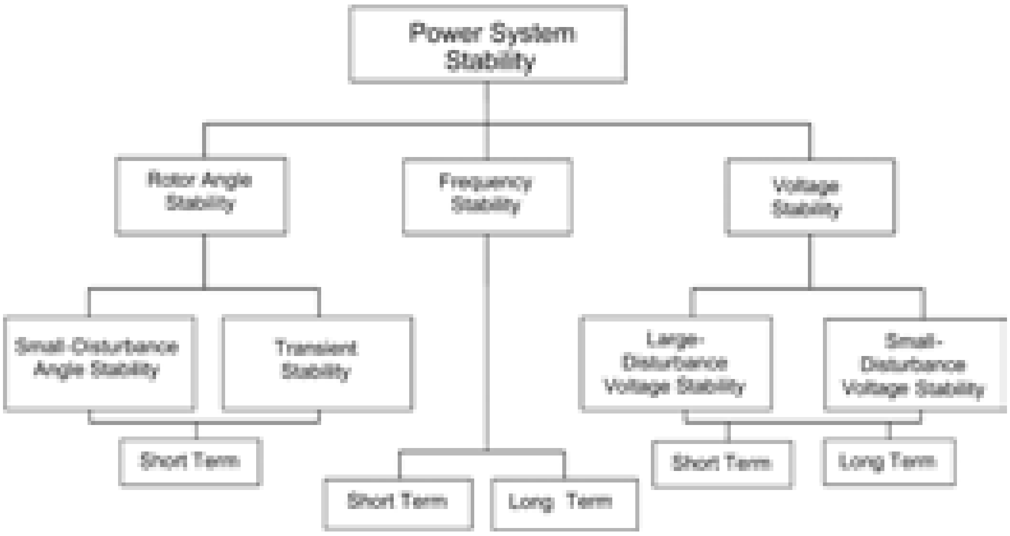

Figure 1.2 Classification of Power System Stability

Bikash and Chaudhuri (2005) explained the appearance of electromechanical oscillations and their reduction in stability as: it started with the operation of synchronous generators in parallel. Oscillations caused by mechanical inertia and power angle characteristics of 1-3 Hz are described as hunting. Low f_e electromechanical oscillations with frequencies ranging from 0.1 Hz to 2 Hz are inherent to electric PS. Problems due to inadequate damping of such oscillations have been encountered throughout the history of PS. As discussed above, the earliest problems, which were experienced in the 1920s, were in the form of spontaneous oscillations or hunting.

The application of continuously acting AVR contributed to the improvement in small-signal (or steady-state) stability. In the 1950s and 1960s, utilities were primarily concerned with transient stability. However, this situation has gradually changed since late 1960s. Significant improvements in transient stability performance have been achieved through the use of high response exciters and special stability aids.

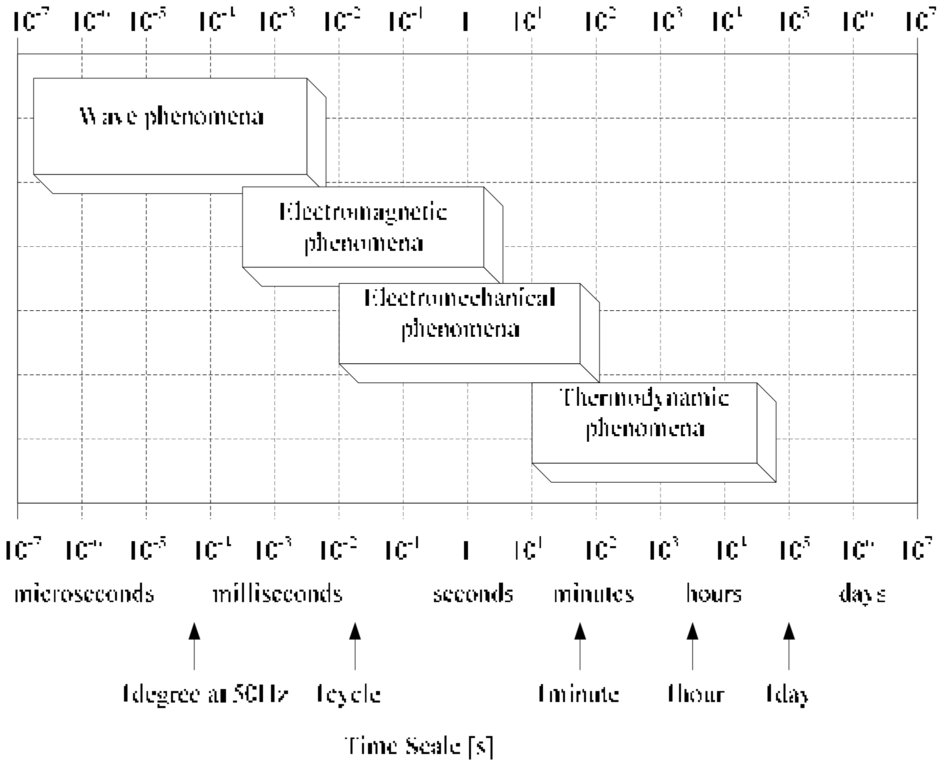

Figure 1.3 Time frame of the basic PS dynamic phenomena

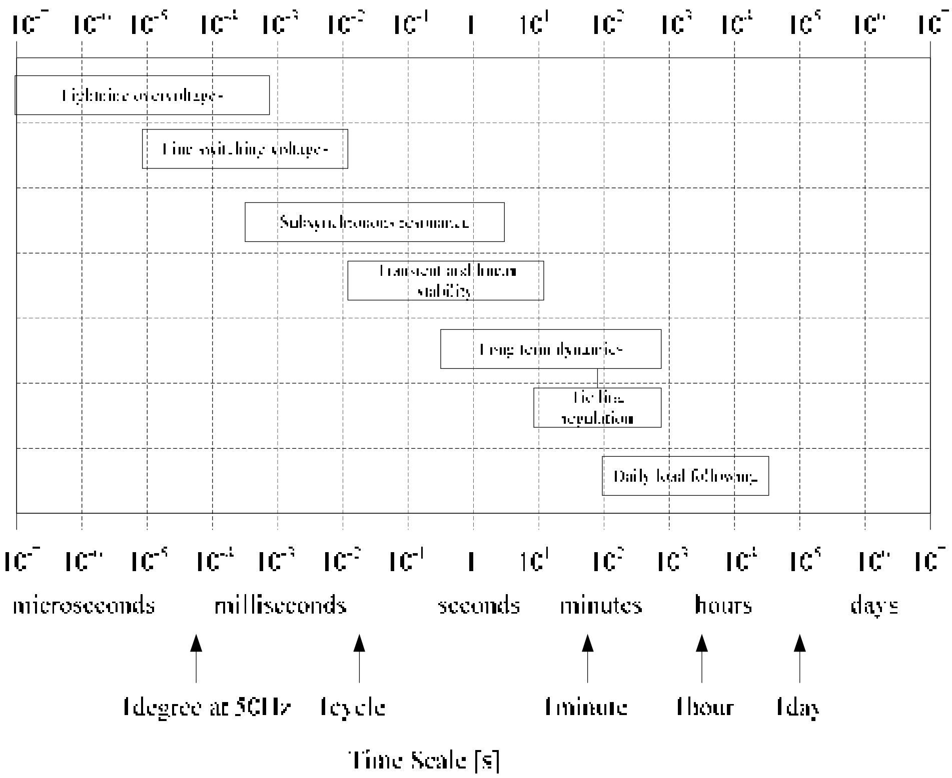

Figure 1.4 Characterization of Transients in PS according to Time Scales or f_e bands

Bikash and Chaudhuri (2005) also have reported the role of inter-area oscillations in many system separation and few wide-scale blackouts by highlighting the incidents occurred at: Detriot Edison (DE), Ontario Hydro (OH), Hydro Quebec (HQ) (1960s, 1985), Finland-Sweden-Norway-Denmark (1960s), Saskatchewan-Manitoba Hydro-Western Ontario (1966), Italy-Yugoslavia-Austria (1971-1974), WECC (1964 and 1996), Mid-continent area power pool (MAPP) (1971, 1972), South East Australia (1975), Scotland-England (1978), Western Australia (1982, 1983), Taiwan (1985), Ghana-Ivory Coast (1985). Besides also the Malaysian system disturbance was reported in August 1996.

It is observed that the weak and poorly damped low f_e electromechanical oscillations occur due to insufficient damping torque in some generators, causing both local-mode oscillations (1 Hz to 2 Hz) and inter-area oscillations (0.1 Hz to 1 Hz) (Bikash and Chaudhuri, 2005).

1.3 Research Problem

Underfrequency Load Shedding (UFLS) is a common practice for electric utilities around the world (Vladimir *et al.*, 1996). It is imperative to save generator from damage at supply end and blackouts from trust as well as economic loss at consumer end or PS network from cascading and islanding. In certain conditions such as; tie line tripping, generator outage, bulk load switching, local mode or inter-area oscillations, various types of LSSs are in practice. For such LSSs, the UFRs found are of modern types like; microprocessor based UFLSR or numerical UFLSR, however traditional or old type of electromechanical as well as solid state LSR (especially in the old power plants) are still being used.

The convergence problem in an emergency condition has been reported by various researchers (Mahmoud *et al*., 1995; Abdullah *et al.*, 2004). They have proposed its improvement by considering effect of; f_e dependent loads, capacitor banks, and synchronous machine or induction motors (in simulation). However besides mitigating such convergence problem, if some other additional factors are taken into consideration, they can help to obtain optimal load shed and to retrieve f_e at its nearest possible nominal value which is the main objective of this research. Such factors can be about software selection, development of LSS, and application of primary controllers. At first instant selection of proper software and insertion of accurate dynamic component parameters especially of f_e dependent loads (this is also due to some software limitations while designing LSS) can help in getting accurate f_e decay response. While developing LSS, selecting total number of LS stages, considering time between two stages (this helps to make discrimination between two steps), selecting amount of LS in first stage can minimize the LS amount. Primary controllers' proper selection and simplification/tuning (because of the probability that same controller could function properly in one or two or three conditions but not for all contingency conditions as used in this research) can help to retrieve f_e at its nearest possible nominal value.

Based on the above problems faced by the PS network in the form of blackouts or islanding or system separation and their solution through LS, the following problem statement is devised for this research:

- OS and/or US are the main attractive parameters for this research to design an optimal dynamic UFLSS. These parameters are found being the cause of convergence problem.

1.4 Significance of Research/Motivation

PS reliability and security practically is not 100% possible, therefore, PS stability has remained challenging task in Reliability, Security and Quality for the PS planners, working committees, and researchers due to; day to day rising demand of power, network congestions, development in technology from source end (generator) to user end (load), increasing transmission U levels, use of different components or devices or appliances from different makes in the same network, and unavoidable natural calamities like; storms, lightning, atmospheric temperature changes etc.

It is very difficult to keep PS stable in catastrophic and unavoidable circumstances. However, through proper planning, PS stability can be achieved through: saving the PS from further big loss i.e. *loading* causing network disconnections, generator trips, islanding, and blackouts and making system easy to be restored. The first could be done by the LS so that some amount of load is cut off to save the further network disconnections, generator trips or turbine-generators (mechanically coupled) from any mechanical damage (leading to permanent loss), which will not only give financial loss but will also be time taking to replace the system. Moreover in such prevailing conditions to find out the alternative source of supply is also challenging task when there is lack of reserve capacity. Thus, optimization of LS (i.e. to minimize the LS amount) is possible to overcome the OS and/or US; as a result the convergence problem could be minimized by incorporating f_e dependent loads, counting primary controllers.

1.5 Research Objectives

This research is mainly focused to overcome problems by optimizing the LS in UF decay condition. However other objectives include:

i) To develop an UFLSR for trapping the cause at its first time and its rectification.

ii) To observe the effect of f_e dependent loads on LS.

iii) To develop an algorithm performing quick action in minimum stages and/or time for complete LS.

iv) To reduce over shedding.

1.6 Scope of the Research

Flow chart in Figure 1.5 shows the scope of this research work. It consists of four parts. First is to sort out the problem, second is to find out the solution through software or tool and method of formulation of the problem and solution, third is to test the solution on some standard systems to obtain optimal results and finally to validate the results by comparing with other methods and testing on other test and utility systems.

The problem is identified through review of literature in order to have the loop holes left by other researchers which needs for its improvement in their work regarding UFLSSs or to develop some new work. For its solution a suitable software or program will be helpful. Convergence problem was found for this research and Commercial *DIgSILENT PowerFactory* 14 (DSPF) software was selected in this regard because of its attractive features.

An algorithm will help to detect and identify the problem and its rectification at an optimal level. For this besides proposed (50-70% LS in first stage; depending upon rate of decay; LS stages minimized to three stages, consideration of f_e dependent loads and least possible load to shed first), swing equation, Newton Raphson (NR) iterative method, and f_e combined with rate of change of frequency ($df_e dt$ or ROCOF) method will be helpful.

To confirm and validate the developed work, it is to be tested on some of the standard systems and compare with the previous work. This research work is tested on some standard systems like IEEE 009, 039 bus and one utility for its 027 number of buses. Finally to validate, the results are compared with some previous work.

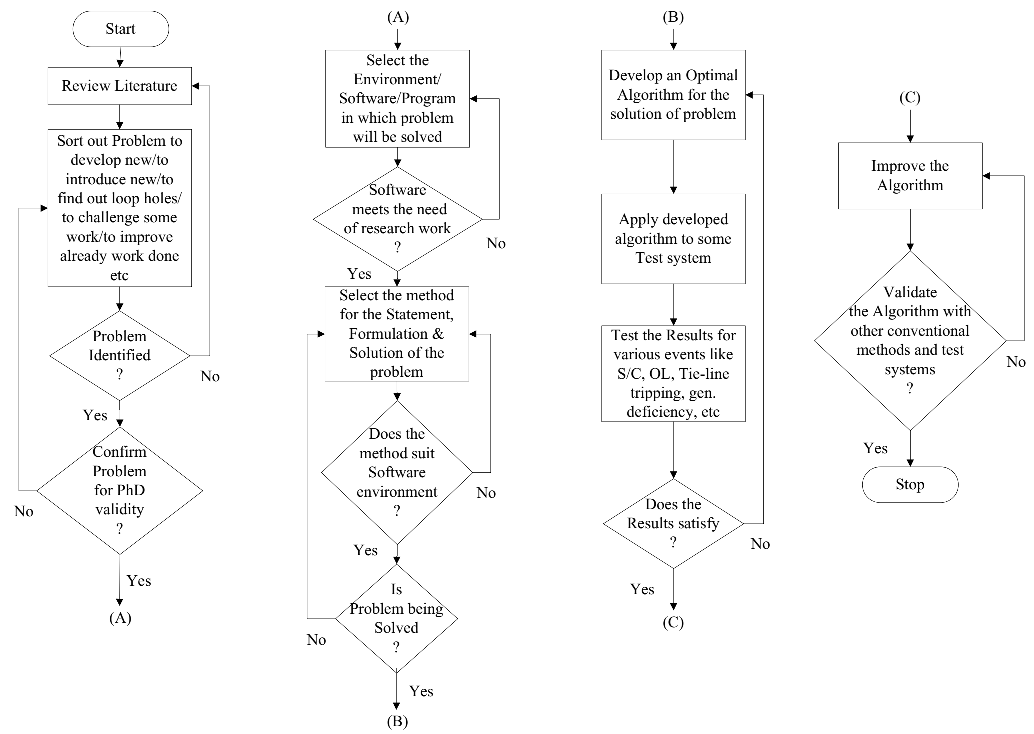

Figure 1.5 Flow chart showing scope of the research work

Limited scope of this research is summarized as:

i) Furnishing UFLSR in DSPF.

ii) Development and implementation of an algorithm for UFLSR.

iii) Use of f_e dependent loads.

iv) Use of modified and simplified primary controllers i.e. GOV and AVR.

v) Testing of developed algorithm in contingencies causing mismatch between electric power supply and demand on IEEE 009, 039 bus systems and in one utility system for 027 number of nodes.

1.7 Thesis Organization

The structure of this thesis is outlined below:

Chapter 2 is mainly concerned with review of literature; elaborating need of LS, problems associated with LS from time to time and their remedial, comparison of different LS methods, selection of software by comparing their different features and applications. The proposed method is also highlighted in this chapter.

Chapter 3 highlights dynamic simulation considerations for stability studies including RMS or time domain analysis or simulation (TDS) in DSPF counting LF execution methods, IC and simulation plus different disturbances generated. PS standard element models like synchronous machine, transmission line, transformer, and f_e dependent load along with standard primary controller models like AVR and GOV are also discussed in this chapter.

Chapter 4 contains frames and primary controllers used in this research. It describes the simplified and modified models of primary controllers like AVR and GOV. It also elaborates them mathematically. To identify controller performances their step response tests are also added.

In chapter 5 modeled dynamic UFLSR is discussed. For validation, along obtained results the application of simplified and modified primary controllers and developed UFLSR is discussed here.

Chapter 6 contains the study cases used in this research. It consist the results of test cases with and without primary control and application of UFLSR with dynamic LSS in different disturbances like load change, generator torque change and/or generator outage.

Chapter 7 will, however, conclude the results obtained in this study and on the basis of those findings some suggestions will be made for future line of research.

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