IMPACT OF DEMAND-SIDE MANAGEMENT ON GENERATING SYSTEMS ADEQUACY ASSESSMENT

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LIST OF ABBREVIATIONS

CLS	Corrective Load Shifting
DLCP	Direct Load Control Programme
DC	Direct Current
DPP	Demand Bidding Programme
DR	Demand Response
DSM	Demand-side Management
DTR	Dynamic Thermal Ratings
EDLC	Expected Duration of Load Curtailments
EE	Energy Efficiency
EENR	Expected Energy Not-Recovered
EENS	Expected Energy Not-Supplied
EES	Expected energy supplied
EFLC	Expected Frequency of Load Curtailments
EIC	Expected Interruption Cost
ELC	Expected Load Curtailments
EP	Emergency Programme
ESS	Energy Storage Systems
ENR	Energy Not-Recovered
EUE	Expected Unserved Energy
FOR	Forced Outage Rate
FLS	Flexible Load Shape
GWh	Giga watt-hour
HL	Hierarchical Level

HLI	Hierarchical Level 1
HLII	Hierarchical Level 2
HLIII	Hierarchical Level 3
h	Hour
int	Interruption
IEAR	Interrupted Energy Assessment Rate
ILP	Interruptible Load Programme
IEEE	Institute of Electrical and Electronic Engineers
IEEE-RTS	IEEE-Reliability Test System
LDC	Load Duration Curve
LFU	Load Forecast Uncertainty
LOLD	Loss Of Load Duration
LOLE	Loss Of Load Expectation
LOLF	Loss Of Load Frequency
LOLP	Loss Of Load Probability
M-BDRPs	Market-Based Demand Response programmes
MCS	Monte Carlo Simulation
MTTF	Mean Times To Failure
MTTR	Mean Times To Repair
MW	Megawatt
MWh	Megawatt-hour
occ.	Occurrence
OPCON	Operating Consideration
PC	Peak Clipping
PRM	Planning Reserve Margin

PLS	Preventive Load Shifting
RBTS	Roy Billinton Test System
RES	Renewable Energy Sources
RTPP	Real-time Pricing Programme
RTP	Real-Time Price
SLG	Strategic Load Growth
TOU	Time-Of-Use
TTF	Time To Failure
TTR	Time To Repair
UK	United Kingdom
VF	Valley Filling
VOLL	Value Of Lost Load
y	Year

LIST OF SYMBOLS

ENR_t	Instantaneous Energy Not-Recovered
ENS_t	Instantaneous Energy Not-Supplied
i	A sampled year
LLD_i	Loss of load duration in hr
LLO_i	Loss of load occurrence
s	The Set of All System States Associated with Loss of Load,
U	The Uniformly Distributed Random Number Between [0,1]
λ	Failure Rate
μ	Repair Rate.
λ_{ij}	The Transition Rate from State i to State j
T	The Average Reserve Shutdown Time Amongst Periods of Need, Excluding Scheduled Outage
S	The Average In-need time Per Occasion of Demand
P_s	The Probability of a Starting Failure Causing All or Part of The Load Unserved
UAC_t	The Unit Available Capacity of The Peaking and Cycling Unit
C	Corresponding Unit Capacity
L_y	The Annual Peak Load
L_w	The Percentage of The Weekly Load in Terms of The Annual Peak
L_d	The Percentage of The Daily Load in Terms of The Weekly Peak Load
L_h	The Percentage of The Hourly Load in Terms of The Daily Peak
D_t	The Original Demand of The System

$\widehat{D}_t$	The Modified System Load Curve Which Results from Implementing DSM Activities
a	The Amount of Peak Reduction
t_1	The Starting Time of the Peak Clipping
t_2	The Final Time of the Peak Clipping
p, q,e	Pre-specified Values
Q_t	The Value of Real Time Production Cost
E_t	The Real Time Value of Emission Rates
f	The Amount of Energy Added to each Off-peak Hour
t_3	The First Hour of Energy Recovery
t_4	The Last Hour of Energy Recovery
K	Any Load, either Additive or Subtractive; that can Result from either Strategic Load SLG or EE Activities Respectively
O	A Parameter that Indicates whether K is Additive or Subtractive Load
t_5	The Starting Time During which Load K is Added or Subtracted and neither Added nor Subtracted.
t_6	The Ending Time During which Load K is Added or Subtracted and neither Added nor Subtracted.
$\overline{D}_t$	The First Modified System Load Curves which Result from Implementing a Load-shifting Activity
$\overline{\overline{D}}_t$	The Second Modified System Load Curves which Result from Implementing a Load-shifting Activity
A	The Percentage of Energy Recovery during Off-peak Hours and its Range is $0 \leq A \leq 1$

a	The First Hour, When the Original Load is Greater than p ($D_t > p$)
b	The Last Hour, When the Original Load is Greater than p ($D_t > p$)
t_7	The First Hour for The Energy Recovery During Off-peak Hour
t_8	The Last Hour for The Energy Recovery During Off-peak Hour
n	The Duration Given by The Difference Between t_7 and t_8
$\dot{D}_t$	The First Modified Load Curve After Subtracting The Instantaneous Energy Not Supplied (ENS_t) from The Original Load
$\ddot{D}_t$	The Second Modified Load Curve After Recovering The Curtailed Load
M	The Amount of Added Energy to each Hour of Recovery Period
ENR_t	The Energy Not Recovered at each Hour of Energy Recovery Period
R	The Percentage of Energy Recovery and its Range is $0 \leq R \leq 1$
$\dot{t}_1$	The First time During the Day When The Original Load Exceeds The System Available Capacity
$\dot{t}_2$	The Last Time During the Day When The Original Load Becomes Equal or Less than System Available Capacity
$\dot{t}_3$	The Starting Time for The Off-peak Recovery of Energy
$\dot{t}_4$	The Ending Time for The Off-peak Recovery of Energy
$\dot{n}$	The Difference Between $\dot{t}_3$ and $\dot{t}_4$
SAC_t	The Instantaneous System Available Capacity
$EENR$	The Expected Energy Not Recovered
X	The Number of Simulation Years

KESAN PENGURUSAN PERMINTAAN-SAMPINGAN PADA PERILAIAN KECUKUPAN SISTEM PENJANAAN

ABSTRAK

Sistem kuasa elektrik perlu menyedari tentang cabaran utama yang masih berlaku, contohnya, penembusan besar-besaran kenderaan elektrik dan beban dan ketidakpastian permintaan-sampingan. Memandangkan kecukupan penilaian bekalan kuasa adalah proses penting dalam fasa perancangan sistem kuasa, program pengurusan permintaan adalah salah satu daripada penyelesaian yang paling cekap dan terpakai untuk dipertimbangkan. Jika kapasiti unit generasi tidak mencukupi untuk memenuhi beban sistem, maka bantuan diperlukan dari sumber alternatif. Strategi peralihan beban adalah satu bentuk program-program pengurusan permintaan, yang secara meluas dilaksanakan dalam penjanaan kuasa elektrik kerana kesan yang besar terhadap kebolehpercayaan dan kecekapan sistem.

Strategi peralihan beban secara konvensional dilakukan dengan menggunakan program peralihan beban pencegahan. Peralihan beban pencegahan dilaksanakan biasanya apabila sistem kuasa mengalami kontingensi yang menjejaskan kebolehpercayaan bekalan kuasa. Kelemahan pendekatan peralihan beban pencegahan adalah tiga kali ganda. Pertama, tenaga yang dipotong tidak boleh pulih sepenuhnya apabila ia melebihi kapasiti yang tidak digunakan dalam tempoh luar puncak. Kedua, pendekatan peralihan beban pencegahan melakukan keratan beban tanpa diskriminasi antara kecukupan dan kekurangan tempoh bekalan kuasa. Ketiga, semakin banyak pemotongan puncak dan tindakan pemulihan tenaga, semakin banyak ketidakpastian program-program pengurusan permintaan. Dalam kajian ini, program pembaikan beban pembetulan dicadangkan sebagai alternatif yang lebih baik kepada peralihan beban pencegahan. Program pembaikan beban pembetulan

tidak mempunyai kelemahan peralihan beban pencegahan kerana ia hanya dilaksanakan apabila terdapat ketidakcukupan bekalan kuasa.

Menjana penilaian kecukupan kapasiti biasanya dilakukan dengan menggunakan model dua keadaan di mana semua unit generasi transit hanya antara keadaan atas dan bawah tanpa mengira jenis penjana. Model dua- keadaan tidak mengambil kira pemisahan sebahagian daripada unit penjanaan haba yang besar. Selain itu, model dua-keadaan itu tidak boleh digunakan dengan betul untuk memodelkan unit penjanaan puncak dan pusingan, kerana mereka tidak mungkin diperlukan apabila keluar dari perkhidmatan disebabkan gangguan yang tidak dirancang. Model hibrid dicadangkan dalam kajian ini, yang mengambil kira semua anggapan di atas, untuk meningkatkan ketepatan penilaian kecukupan kapasiti.

Apabila penyelenggaraan terancang dipertimbangkan, tahap risiko lebih dikompaunkan disebabkan pengurangan margin rizab pada masa yang berlainan dalam tahun sesuatu. Beban masa depan yang tidak menentu memerlukan rizab kapasiti yang lebih tinggi daripada beban tetap. Oleh itu, ketidakpastian ramalan penyelenggaraan dan ramalan beban yang dirancang adalah pertimbangan yang tidak dapat dielakkan. Kedua-dua pertimbangan ini diambil kira untuk menyiasat kekukuhan pembaikan beban pembetulan berbanding dengan peralihan beban pencegahan. Seperti yang dijangkakan, kajian ini menyiasat impak peralihan beban pencegahan dan pembaikan beban pembetulan sebagai alternatif kepada unit puncak.

Penemuan dari kajian ini menunjukkan bahawa pembaikan beban pembetulan yang dicadangkan dapat melakukan lebih baik daripada peralihan beban pencegahan dan, oleh itu, strategi yang lebih kuat untuk dilaksanakan. Di samping itu, penemuan menunjukkan bahawa model hibrid membawa kepada penilaian yang lebih tepat dan realistik kecukupan bekalan daripada model dua keadaan. Penggunaan pembaikan beban pembetulan cenderung untuk mengatasi kesan beban yang dirancang dan penyelenggaraan yang dirancang. Oleh itu, pembaikan beban pembetulan adalah alat yang diguna pakai untuk diambil dan diintegrasikan ke dalam pertimbangan sedemikian untuk mengurangkan secara mendadak kemerosotan-kemerosotan tenaga yang tidak dibekalkan.

Simulasi Monte Carlo berurutan telah digunakan dalam kajian ini. Kajian ini dijalankan menggunakan sistem ujian kebolehpercayaan IEEE.

IMPACT OF DEMAND-SIDE MANAGEMENT ON GENERATING SYSTEMS ADEQUACY ASSESSMENT

ABSTRACT

Electrical power systems have to be aware of the major challenges that still lie ahead, for example, the massive penetration of electrical vehicle and load and supply-side uncertainties. Since, the adequacy of power supply assessment is an important process in power systems planning phase, demand-side management (DSM) programme is one of the most efficient and applicable solution to be considered. If the generation unit's capacity is insufficient to meet the system load, then assistance is required from alternative sources. A load shifting strategy is a form of DSM programme, which is widely implemented in electrical power generation due to its considerable impact on system reliability and efficiency.

The load shifting strategy is conventionally performed using the preventive load shifting (PLS) programme. PLS is implemented usually when power systems experience contingencies that jeopardise the reliability of the power supply. The disadvantages of the PLS approach are threefold. First, the clipped energy cannot be totally recovered when it is more than the unused capacity of the off-peak period. Second, the PLS approach performs load clipping without discrimination between adequacy and inadequacy of power supply period. Third, the more number of peak clipping and energy recovery action, the more DSM programme uncertainty. In this study, the corrective load shifting (CLS) program is proposed as the better alternative to PLS. The CLS program has none of PLS disadvantages because it is implemented only when there is power supply inadequacy.

Generating capacity adequacy assessment is usually performed by using two-state model in which all generation units transit only between up and down states regardless of the types of generators. The two-state model does not take the partial

outage of the large thermal generation units into consideration. As well, the two-state model cannot be properly used to model peaking and cycling generation units, as they may not be needed when they are out of service due to an unplanned outage. A hybrid model is proposed in this study, which takes into consideration all above assumptions, to increase the accuracy of generating capacity adequacy assessment.

When planned maintenance is considered, the risk level is approximately compounded because of the reduction in reserve margin at different times of the year. Uncertain future load requires a higher capacity reserve than fixed load. Thus, the planned maintenance and load forecast uncertainty (LFU) are unavoidable considerations. These two considerations are taken into account to investigate the robustness of CLS comparing to PLS. As will, this study investigates the impact of PLS and CLS as alternatives to peaking units.

The findings from this thesis show that the proposed CLS can perform better than PLS and is, therefore, a more robust strategy to be implemented. In addition, the findings show that hybrid model leads to more accurate and realistic assessment of adequacy of supply than two-state model. The application of CLS tends to significantly overcome the effects of LFU and planned maintenance. Thus, CLS is an applicable tool to be adopted and integrated into such considerations to significantly mitigate the expected energy not-supplied deterioration.

The sequential Monte Carlo simulation (MCS) was employed in this study. The study was conducted using the IEEE-reliability test system (RTS).

CHAPTER ONE

INTRODUCTION

1.1 Background

Modern electrical power systems must meet constantly changing power consumption requirements with a satisfactory level of reliability, environmental friendliness and quality (Billinton, 2013). Nevertheless, meeting these challenges has become progressively difficult owing to the increase in electricity demands caused by population and industrial growth (Dehnavi and Abdi, 2017). Thus, electrical power grids must be highly integrated to cope with the uncertainty of load and supply. The International Energy Agency estimated that the global power energy demand in 2030 will be more than 50% higher than that in the present (Freeman, 2005), for example, due to the massive implementation of the electric vehicle (Martínez-Lao et al., 2017). In addition to this issue, the infrastructure investments required to support the growing global electricity demand will be massive because ageing power system components will have to be replaced.

Thus, the usual practices aimed at balancing electricity supply and demand have to be examined closely. Reduction of power consumption is worth more than power generated (Saini, 2004). For example, after accounting for transmission and distribution along line losses, one unit of electricity saved at the consumer side is worth 10% more of the unit saved at the generator side. Although system reliability can be maintained by increasing investment into the system, the cost of investment must be justified by the value of reliability improvement. In this sense, the reliability and economic constraints are opposite (Billinton, 2013). Thus, finding an optimal managerial decision at the planning phases is beneficial for ensuring customer satisfaction at all times.

As a whole, the load shifting programmes investigated in this thesis fit into the wider agenda of DSM. Since DSM programmes have received considerable attention in recent years due to their significant impacts on reliability, DSM programmes are expected to be implemented substantially in the next few decades to satisfy the requirements of new challenges, such as the intermittent nature of renewable energies, global environmental concerns and economic constraints. These programmes should be considered in the planning and operation phases of electrical power systems and must be integrated with generation-side management to maintain the reliability and increase the efficiency of power systems.

1.2 Power Systems Reliability

The electric utility industry is obligated to supply efficient and reliable electric services to customers as economically as possible (Li, 2013). However, it is unpractical to design and construct fully reliable electrical power systems. Power system planners attempt to design a reasonable level of reliability at an acceptable initial and running cost. The reliability of power systems is a measure of the overall ability of the system to achieve its basic function. System reliability is divided into two: system adequacy and system security as shown in Figure 1.1.

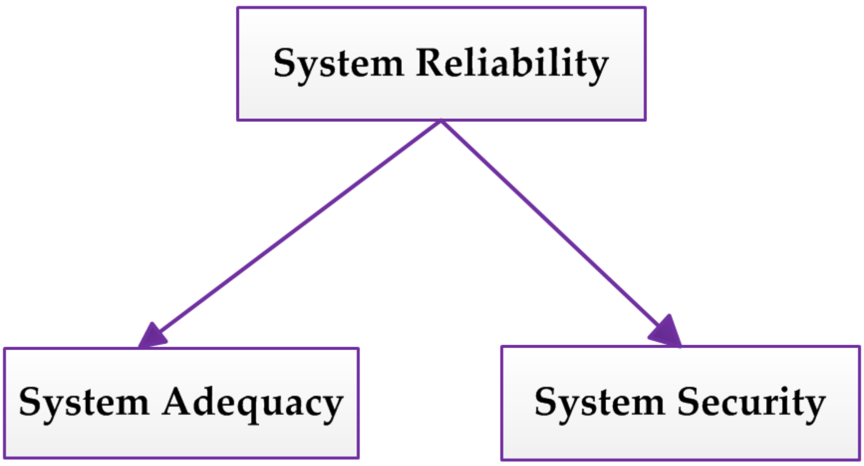

Figure 1.1 Division of system reliability (Billinton, 2013)

System adequacy refers to the existence of sufficient facilities to meet the consumer demand. These facilities involve the generators to generate sufficient energy, the associated transmission lines to transmit the required energy to the distribution systems and the distribution networks to transport the energy to customers. Therefore, system adequacy does not include system disturbances. Security relates to the ability of the system to respond to disturbances.

Electric power systems are generally categorized into three hierarchical levels (HLs) of generation, transmission and distribution as shown in Figure 1.2.

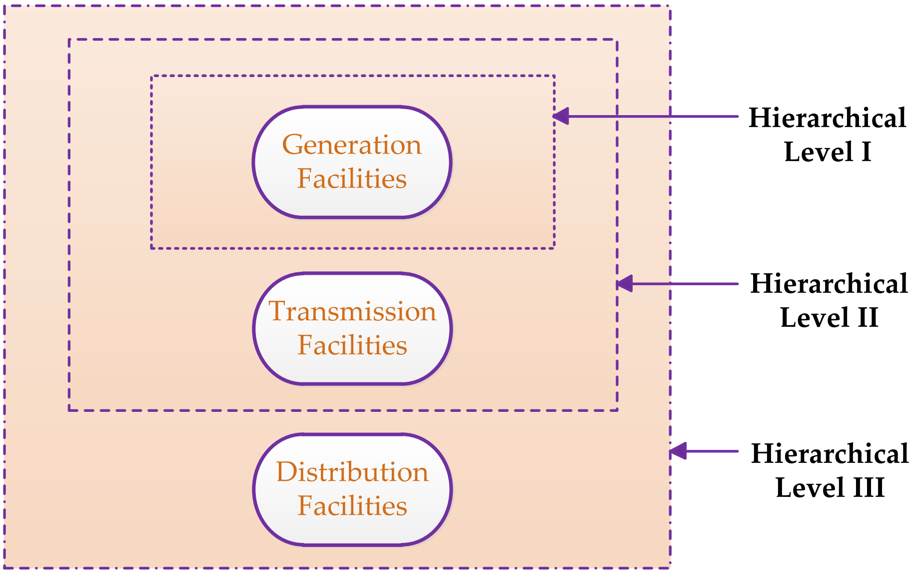

Figure 1.2 Hierarchical levels (Billinton, 2013)

HL1 involves the analysis of the generation facility, HL2 considers the analysis of the generation and transmission facilities and HL3 considers the analysis of an additional distribution facility. Only HL1 and HL2 studies are regularly performed given that complete HL3 studies are highly complex because of their large problem scale. Thus, the distribution network is normally analysed individually and separately from the generation and transmission systems. Electrical power reliability is usually calculated in terms of certain reliability indices. These are usually measured to evaluate the level of reliability worth and cost at specific zone in electrical power systems, therefore, it is significant to tabulate these indices as in Appendix A (Billinton, 2013).

HLI reliability assessment is defined as generating capacity adequacy evaluation. One of the power system reliability investigation studies is the generating systems adequacy study and it is concerned only with the ability to satisfy customer demand (Billinton, 2013). Generating systems adequacy is the ability of generation systems to provide a sufficient and continuous supply of electricity to the users' demands. The ability of transmission and distribution system to move the supplied energy to the end-user is neglected in HLI assessment. In this study, transmission and distribution systems are not considered and assumed fully reliable. Thus, this thesis focuses on the HLI assessment.

Generating capacity adequacy assessment is usually performed by using two, three and four-state model. In two-state model, all generation units transit only between up and down states regardless of the types of generators. The three-state model takes the partial outage of the large thermal generation units into account. Four-state model is properly used to model peaking and cycling generation units.

Expected values based on probabilistic assessment are used to assess the level of adequacy, namely loss of load expectation (LOLE), expected energy not-supplied (EENS), loss of load frequency (LOLF) and loss of load duration (LOLD).

1.3 Overview of DSM Techniques

In modern and deregulated power systems, distribution companies bid for electricity prices to maximise their profits. Electricity prices fluctuate in accordance with real-time electricity demands. Specifically, electricity prices increase as demand rises and vice versa. Prudent power system management is necessary to ensure the constant supply and trading of electricity. The management of power systems is classified into supply-side management and demand-side management (DSM). Both strategies are useful for mitigating contingencies, increasing network loading capacity and reducing peak loads. In contrast to supply-side management, DSM is concerned with electrical load levels and usage patterns and is therefore unaffected by external factors. Therefore, DSM becomes more beneficial than supply-side management as electricity demands continue to grow at a rate that exceeds the expansion rate of power systems. As a result, many utilities consider DSM programmes as favourable options for power generation because of their remarkable technical, environmental and economic impacts.

DSM is an initiative implemented by electricity utilities to encourage consumers to adopt procedures and practices that are advantageous from the system and customer views (Gellings, 2017). This initiative includes analysis, planning and implementation of utility activities to affect load shapes in either time pattern or magnitude (Limaye, 1985). DSM control mechanism is divided into two, direct and indirect control (Saini, 2004). DSM practices include any activity that aims to change load shapes by influencing the electricity consumption behaviour of consumers (Limaye, 1985).

Based on the objectives achieved by DSM, the various DSM techniques are shown in Figure 1.3. Peak clipping (PC) refers to the reduction in on-peak load. Valley filling (VF) involves building loads during the off-peak load curve period (Gellings, 2017). Load shifting (LS) refers to the combination of peak clipping/load curtailment and valley filling measures. It works by either clipping loads from the

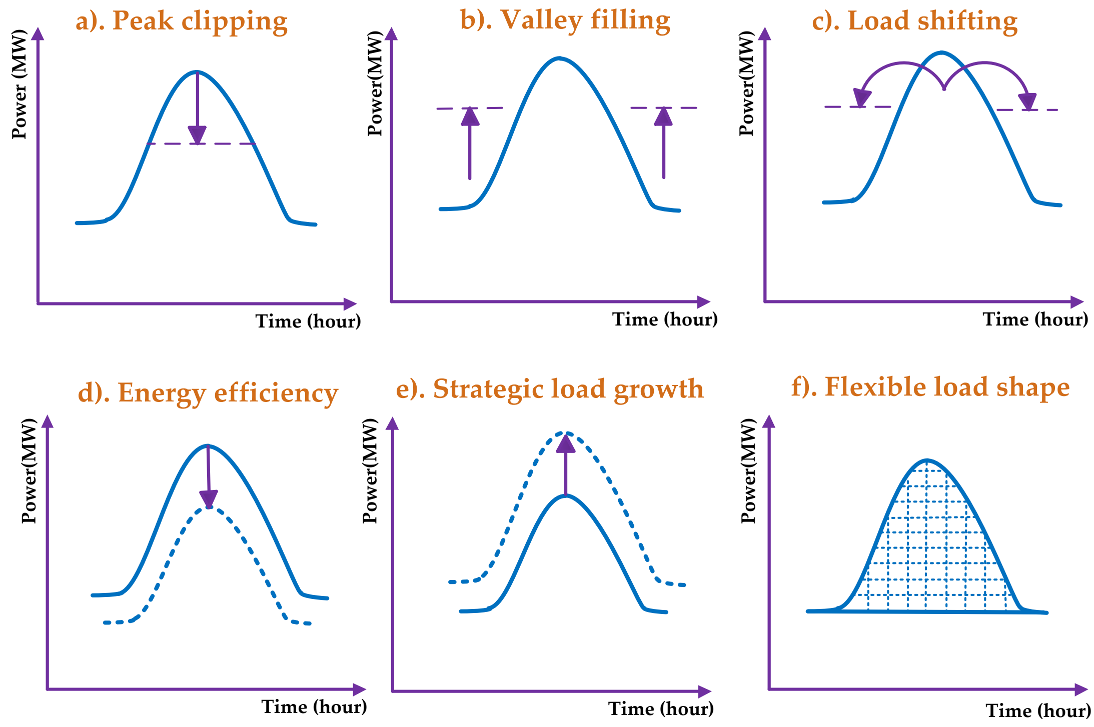

Figure 1. 3 Various DSM techniques based on the achieved objectives (Gellings, 2017)

on-peak period or curtailing the load due to adequacy efficiency and filling them during the off-peak period. Energy efficiency (EE) refers to lessening the total load demand by enhancing the efficiency of energy use. Examples of energy-efficiency programmes include house-appliance efficiency enhancement and weatherisation (UNIDO, 2017). Strategic load growth (SLG) is defined as increased electrical energy load and is normally induced by utilities through dual fuel heating, heat pumps, thermal storage (thermal energy is stored during off-peak times for use during on-peak periods) and promotional rates. SLG is sometimes unavoidable because of the general increase in electricity demands, especially with the advent of electric vehicles of modern power systems (Gellings, 2017) or air conditioning in warm countries (Juaidi et al., 2016). Flexible load shape (FLS) refers to particular tariffs with opportunities to flexibly control consumer equipment (Gellings, 2017).

Demand response (DR) programme involves a short-term load manipulation programme. DR usually implements to change the electric usage of costumers in response to the following (1) The reliability of power systems is being in jeopardy (2) changes in the real-time price of electricity (Qdr, 2006). DR is normally performed through peak clipping, valley filling or load-shifting activities or any combination of these techniques (Gellings, 2017). DR is also known as flexible load shape because of the flexibility exhibited by the activities. Given that, one of the advantages of DR is that it affects load directly. Excluding EE and SLG, other DSM techniques are gradually being replaced by DR programmes in the new electricity market environment (Walawalkar et al., 2010). DR is performed using either valley filling to build loads during off-peak periods or peak clipping to reduce loads during on-peak periods or load shifting, which combines valley-filling and peak-clipping activities (Gellings, 2017). Figure 1.4 shows DR programmes.

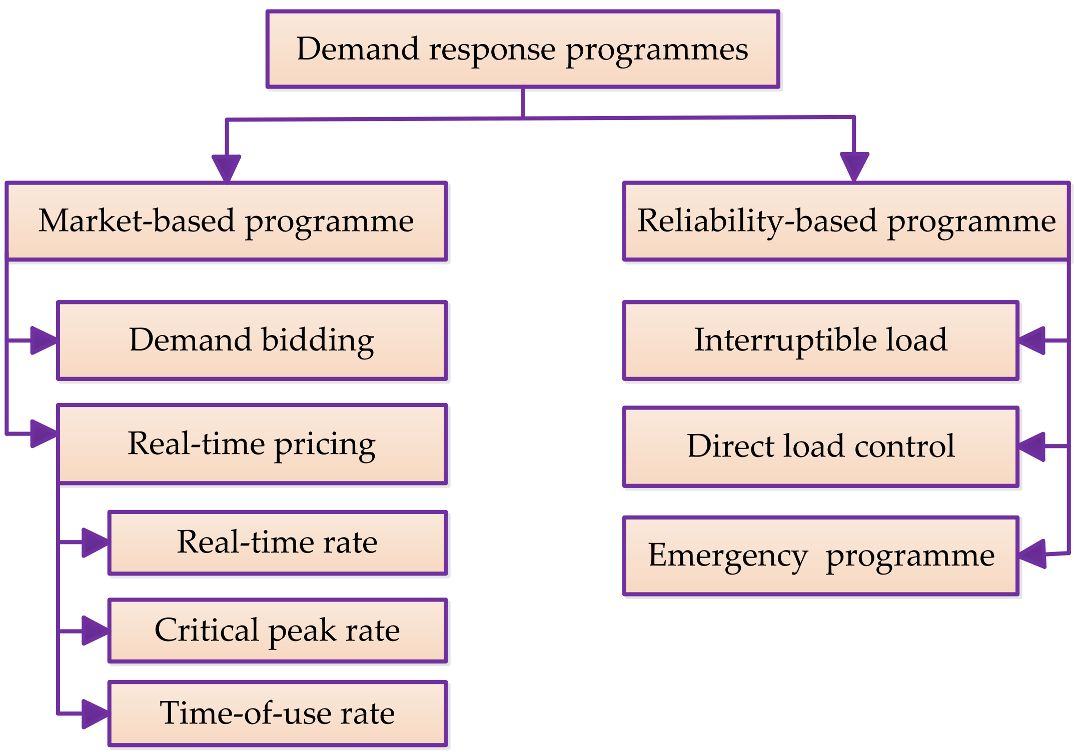

Figure 1.4 Various DR programmes (York and Kushler, 2005)

As shown in Figure 1.4, DR programmes are further divided into either reliability-based DR programmes (R-BDRPs) or market-based DR programmes (M-BDRPs) (York and Kushler, 2005). In R-BDRPs, consumers decrease their loads and/or voluntarily or involuntarily participate in controlled appliance use. In turn, consumers derive economic incentives by enrolling in this programme. By providing real-time electricity market prices, M-BDRPs provide consumers with the options to adjust electricity consumption.

R-BDRPs consist of the interruptible load (IL) programme, direct load control (DLC) programme and emergency programme (EP) (Qdr, 2006). Large industrial and commercial consumers who can shut down their load for a short duration usually apply ILP. Consumers receive discounted electricity rates as compensation for accepting service interruptions. However, they can also be penalised if they do not participate in the programme when required. While in DLC programme, the utility is allowed to directly interrupt or reduce consumer power supply during peak demand times after consumers are notified. In return, interrupted consumers receive compensation. In EP, consumers are given incentives to reduce their demand during system contingencies. In contrast to the interruptible load programme, this programme does not impose any penalties if consumers cannot participate.

M-BDRPs consist of the demand bidding programme (DPP) and real-time pricing programme (RTPP) (Qdr, 2006). DDP allows major consumers to bid for specific load curtailments. Consumers stay at a fixed rate, and they receive high payments when wholesale electricity prices are high. Electricity production costs fluctuate over time and average system costs are fixed without considering its undesirability, particularly for large commercial and industrial consumers. To address these issues, the RTPP is introduced and implemented through the following:

a) Time-of-use (TOU) rate. This rate is a predefined electricity price offered over a wide range of time periods, that is, seasonal, monthly, weekly or daily. The rate is voluntary and reflects basic production costs to decrease consumer demands during periods of high prices (Qdr, 2006).
b) Critical peak rate. This rate offers consumers dynamic pricing that reflects actual market costs during critical peaks. This rate is usually offered a day ahead of the expected peak and is predefined but may be dynamic when necessary. Critical peak pricing rates can be used to improve power system reliability because they reflect the system state. Hence, if appropriate critical peak pricing signals are sent out, consumers may participate by decreasing load during system-stress events (York and Kushler, 2005).
c) Real-time price (RTP). In this programme, consumers pay rates that are a function of actual market rates. Prices are usually supplied hourly or a day ahead to enable preplanning. Thus, rates will vary depending on the fluctuations in electricity supply (York and Kushler, 2005).

1.4 Problem Statement and Research Gap

DSM has been reviewed by many studies from various points of views. Nevertheless, a joint investigation on the impacts of DSM on the economic performance, environmental friendliness, operation and reliability of power systems is unavailable. Such an investigation is timely given that current power systems are required to be holistic and should consider engineering and societal requirements. Although past surveys and studies on individual issues of power systems are commendable and important, a joint analysis will provide novel insight on the impacts of DSM on modern power systems. Such insight is particularly crucial given the modern advent of smart grid technologies. The joint impacts of DSM on power systems are necessary in the related field.

During generation system expansion exercise, system planners can implement DSM programme instead of constructing new generation plants to meet load demand (Teh et al., 2018). If the generation unit's capacity is insufficient to meet the system load, then assistance is required from alternative sources. Since the main purpose of the DSM programme is risk mitigation, an accurate evaluation of the DSM impact on generating system adequacy is important (Patton and Singh, 1984). A load shifting strategy is a form of DSM programme, which is widely implemented in electrical power generation due to its considerable impact on system reliability and efficiency. It functions by clipping the load demand that is above an operator-defined level, at which time is known as peak period, and replaces it at off-peak periods. The load shifting strategy is conventionally performed using the preventive load shifting (PLS) programme. PLS is implemented usually when power systems experience contingencies that jeopardise the reliability of the power supply. The disadvantages of the PLS approach are threefold. First, the clipped energy cannot be totally recovered when it is more than the unused capacity of the off-peak period. Second, the PLS approach performs load clipping without discrimination between adequacy and inadequacy of power supply period. Third, the more number of peak clipping and energy recovery action, the more DSM programme uncertainty. Considerable works have been performed for the adequacy assessment of generating system incorporating PLS. However, so far there are no specific modelling framework and analysis in the literature that has addressed on a quantitative basis the impact of corrective actions of the energy curtailed by using dynamic load shifting or corrective load shifting(CLS) on generating system adequacy.

In this study, the corrective load shifting (CLS) program is proposed as the better alternative to PLS. The CLS program has none of PLS disadvantages because it is implemented only when there is power supply inadequacy. As such, this presents gap that this thesis intends to fill.

Generation units are divided into three types; base load, cycling and peaking units. Base load units operate consistently to generate the electrical power needed to satisfy base load demand. These units are the most economical to operate and stop only for maintenance or unplanned outages. Peaking units operate only during high demand when load level surpasses the power supply of base load units. These units have a much higher production cost than base and cycling units. Due to this, the duty cycle of peaking units is shorter than duty cycle of base load units. Generating capacity adequacy is usually assessed by using two-state model in which all generation units transit only between up and down states regardless of the types of generators. A large thermal generating units can operate at a partial-capacity state (Li, 2013). The two-state model does not take the partial outage of generation units into account. As well, the two-state model cannot be properly used to model peaking and cycling generation units, as they may not be needed when they are out of service due to an unplanned outage. Moreover, when they are in service, periods of service could be interrupted by reserve shutdown. To deal with this issue, hybrid model is required by considering all mentioned models to find an accurate assessment of generating capacity adequacy. As such, this presents another gap that this thesis intends to fill.

In order to do so, this thesis proposes an algorithm to simulate the dynamics load shifting during the instantaneous interruptions on the real-time/moment-to-moment basis. Comparisons of reliability indices of both PLS and CLS computed are presented in the presence of planned maintenance and load forecast uncertainty (LFU). A quantitative assessment is implemented in this thesis to find a complete picture of the implications of using DSM resources to provide adequacy of supply as alternatives to generation facilities. A new index is presented which is called expected energy not-recovered (EENR) to show the expected average amount of energy in a year that cannot be recovered during the off-peak day period (24 hours) of energy recovery actions.

1.5 Research Aim and Objectives

DSM programmes provide various advantages to the electrical power systems and this has no doubt attracted a considerable amount of research works. Majority of existing literature has focused on the economic benefits achieved by DSM implementing to both utilities and customers. Currently, the development of DSM is still at an early stage. However, no framework and modelling for quantitative assessment of the DSM contribution to the generating systems adequacy from corrective and preventive risk actions point of view are available, particularly taking into consideration the dynamic conditions of generating units and load behaviour. The DSM models, which are available in literature, do not consider the system capability of recovering the instantaneous energy shortfall per every single event and during the same 24 hours of interruption period. This study, as well, aims to provide a new index namely EENR that reflects the amount of energy cannot be recovered per a year. This index will provide a significant indicator to power systems planners.

Thus, the research that is presented in this study aims to establish a comprehensive framework for the assessment of the contribution of DSM, as preventive and corrective actions, to generating systems adequacy in the presence of duty cycle and failure initiation of peaking and cycling of generation units, the partial outage of the large thermal generation units, planned maintenance and LFU.

The specific objectives of this thesis are listed as follows.

a) To find a new model of load shifting as a corrective action after generating systems inadequacy incidents. Then, to assess the impact of load shifting as corrective and preventive actions on the generating capcity adequacy assessment.
b) To develop new hybrid model to assess generating capacity adequacy accurately by consideration the two, three and four-state model.
c) To find a systematic comparison between the corrective and preventive actions of load shifting in presence of planned maintenance and LFU using hybrid model.

1.6 Scope of Research

The scope of the research work that is presented in this thesis concentrates exclusively on the generating capacity adequacy (or HLI) assessment incorporating with selected DSM activities. As the mechanism of DSM control is divided into two, direct and indirect control, this study focuses on direct control only. This assessment involves the following considerations: (1) duty cycle and failure initiation of peaking and cycling generation units, (2) The partial outages of generation units, (3) planned maintenance, and (4) LFU. Probabilistic approach is used by utilising sequential Monte Carlo simulation (MCS) to calculate reliability indices. The system risk model is acquired by combining the generation model with the load model. Thus, risk indices are obtained. Sequential MCS simulates the actual process and the random behaviour of the generation systems in HLI assessment. The reliability indices are obtained by combining the load model with the generation model and then to find power inadequacy in terms of energy amount, duration, frequency and duration per each interruption.

1.7 Thesis Structure

In accordance with the aforementioned objectives, the thesis is structured as five chapters, which are summarised as follows:

Chapter one gives a general overview of the background of the research work in this thesis. Chapter two presents a literature review for DSM impact on electrical power systems. Chapter three introduces the methodology of the proposed case studies in this thesis. Chapter four gives a result of the proposed case studies. Chapter five provides the main conclusions of this thesis. Additionally, possible directions and suggestions for future work are discussed.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter is an attempt to perform a different kind of analysis that addresses the gaps. A review of various initiatives, techniques, impacts and recent developments of the DSM of electrical power systems are presented. The potential benefits derived by implementing DSM in electrical power networks are presented as well. An extensive literature survey on the impacts of DSM on the reliability of electrical power systems is provided. The research gaps within the broad field of DSM are also identified to provide directions for future work.

Assessing the effects of DSM on electrical power systems is useful to the field of integrated resource planning because this field requires the extensive investigation of the potential mutual benefits achieved by DSM. Therefore, the general impacts of DSM on reliability was considered to enable readers to keep abreast of recent research on electrical power systems.

A considerable amount of literature has been published on DSM review from various points of views. These studies are summarised chronologically in Table 2.1

Table 2. 1 Outline of DSM past review

Sources	Main contribution
(Morgan and Talukdar, 1979)	Direct load control impact on electrical power systems
(Bellarmine, 2000)	Interactions of DSM with renewable energy sources (RES) in the Australian national electricity market
(Kirby, 2006)	Advantages and disadvantages of utilizing load response regarding reliability services.

Table 2.1 Continued

Sources	Main contribution
(Strbac, 2008)	Challenges and benefits of DSM measures faced by the UK electricity system
(Boshell and Veloza, 2008)	DSM implementation experience in Europe, Japan, USA, Mexico, Brazil and Costa Rica
(Mohamed and Khan, 2009)	Electrical energy management techniques in industrial sector at supplier and consumer sides
(Palensky and Dietrich, 2011)	Taxonomy of DSM
(Zhang and Li, 2012)	DR classification, implementation mechanisms, impacts on electrical power systems and cost-benefit analysis
(Conchado and Linares, 2012)	The economic benefits of DSM
(Bradley et al., 2013)	Costs and benefits of DR in the UK
(Aghaei and Alizadeh, 2013)	Classifications, benefits and successful experiences of DR throughout the world
(Ming et al., 2013)	A historical review of DSM in China on management and operation techniques
(Warren, 2014)	Global historical impacts of DSM and the UK's DSM policy and its interaction
(Barbato and Capone, 2014)	The most relevant studies on optimization methods for DSM of residential consumers
(Mostafa et al., 2014)	Energy management systems at utility and customer side
(Pinson and Madsen, 2014)	DR benefits and challenges
(Siano, 2014)	DR potentials and benefits in smart grids
(Shariatzadeh et al., 2015)	Application and implementation strategies of DR in a smart grid
(Behrangrad, 2015)	Various DR business models for different electricity market
(Hussain et al., 2015)	DR benefits, techniques, pricing signals and optimization
(Vardakas et al., 2015)	Various DR schemes, programs and various optimization models

Table 2.1 Continued

Sources	Main contribution
(Deng et al., 2015)	DR mathematical models, problems and potential challenges in smart grid
(Zhou and Yang, 2015)	DSM and DR programs of China's power industry reform
(Wang et al., 2015)	DR architectures and incentive policies in North America, Australia and Europe.
(Khan et al., 2015)	DSM optimization techniques used in smart grids
(Khan et al., 2016)	Dynamic pricing schemes of DR in a smart grid
(Shoreh et al., 2016)	Applications of DR in the industrial sector
(Dong et al., 2016)	The challenges of DR implementation in China from the perspective of technological and policy
(Haider et al., 2016)	Challenges of residential DR systems in smart grid
(Zehir et al., 2016)	DR programs and RES impacts on the consumer level in Turkey
(Boßmann and Eser, 2016)	Different aspects of DR measures and energy models
(Esther and Kumar, 2016)	Various optimization techniques of DSM in the residential sector
(Sharifi et al., 2017)	Demand-side tools in the electricity market
(Alasseri et al., 2017)	DSM actions impact on the growth of per capita electricity consumption in Kuwait
(Wang et al., 2017b)	Basic concept and analysis of integrated DR in multi-energy systems
(Meyabadi and Deihimi, 2017)	Categorization of DSM strategies, expressions and methodologies
(Good et al., 2017)	DR classification, barriers, analysis, and enablers in a Smart grid
(Meyabadi and Deihimi, 2017)	DSM methodologies, concepts, theoretical framework and categorization

Nevertheless, a joint investigation on the impacts of DSM on the economic performance, environmental friendliness, operation and reliability of power systems is unavailable. Such an investigation is timely given that current power systems are required to be holistic and should consider engineering and societal requirements. Although past surveys and studies on individual issues of power systems are commendable and important, a joint analysis will provide novel insight on the impacts of DSM on modern power systems. Such insight is particularly crucial given the modern advent of smart grid technologies. In view of the identified gaps, this literature review focuses on studies on the joint impacts of DSM on power systems.

2.2 Impacts of DSM on Power Systems

The impact of DSM on power systems is reviewed from the perspectives of the electricity market, environment and power system operation and reliability.

2.2.1 Electricity Market

Consumers mostly derive economic benefits in the form of incentive payments from participating in various DSM programmes (Qdr, 2006). From the utility side, these economic benefits are usually operating costs, decreased load losses and increased system efficiency (Delgado, 1985). Furthermore, the system will be most efficient if variations in power demand are kept as small as possible (Albadi and El-Saadany, 2008). With regard to customer's side, DSM decreases cost by giving options and more control choices to customers. Society in general also gets advantages from technology trend enhancement and efficient use of resources (Delgado, 1985).

The impacts of DSM on the electricity market model have also been widely investigated. Industrial responsive loads have been modelled to maximize the efficiency of hydroelectric power generation (Moghadam et al., 2014). Economic dispatch and DR have been integrated to enhance system efficiency (Nguyen et al., 2016). Unit commitment (UC) and DSM have been combined to improve electricity market performance and decrease operational system cost (Magnago et al., 2015, Nelli, 2010, Govardhan and Roy, 2014, Toh and Gooi, 2012, Aghaei et al., 2016, Yousefi Ramandi et al., 2016). An investigation on the impacts of DSM towards energy and reserve market scheduling problem has been addressed (Darvish et al., 2015). An integration of DSM and distributed energy storage systems has been evaluated to improve the efficiency of the power grid (Nguyen et al., 2015). Dynamic economic dispatch, which incorporates different penetration levels of wind energy, has been utilised to evaluate the impact of DSM on operation cost (Alham et al., 2017). A joint model of emission dispatch and multi-objective dynamic economic incorporating with DSM scheme has been proposed to explore the benefits to both utilities and generating companies (Lokeshgupta and Sivasubramani, 2018). The time-of-use rate has been implemented on distribution networks with large industrial and commercial loads to simultaneously decrease utility and consumer costs (Kinhekar et al., 2014). Using a real-time pricing technique, energy management scheme has been proposed to integrate energy provider and multiple energy hub operators (Ma et al., 2018).

In electricity market environment, DR program provides financial risk management solutions for real-time pricing (Yang et al., 2015) and lead to lessening wholesale electricity prices (Qdr, 2006) by shifting demand from high-cost period to less cost period, leading to lower production costs. The DR programme can relieve market power in the case of the limited power supply and transmission-line constraint violations (Jalili et al., 2017). Moreover, the DR programme also reduces the market risk of consumers and suppliers and the uncertainty and fluctuation of prices (Abaravicius, 2007, Feuerriegel et al., 2012, Zhang and Li, 2011). Meanwhile, this has a positive effect on improved markets performance. As a result, DR programs help to mitigate suppliers' ability to practice market power by increasing electrical power prices above production costs (Qdr, 2006).

2.2.2 Environment

The decrease in energy production reduces greenhouse gas emissions and thus attenuates environmental damage (Martins et al., 1996, Mollahassani-pour et al., 2015, Mollahassani-pour et al., 2017, Reddy and Parikh, 1997, Shrestha and Marpaung, 1999). Such a decrease can be achieved by ensuring the optimal scheduling and operation of base generation units and reducing the frequency of shutdowns and startups of generators because generator startup and ramping require fuel burning without electricity generation. Hence, decreasing startup and ramping frequencies can reduce emissions (Holland and Mansur, 2008, Abaravicius and Pyrko, 2006). The impact of DSM on environmental performance has been addressed in the literature. For example, the possible environmental benefits of load management by Swedish electrical utilities have been determined (Abaravicius and Pyrko, 2006). A joint model of emission dispatch and multi-objective dynamic economic incorporating with DSM action has been proposed (Lokeshgupta and Sivasubramani, 2018). Power generation expansion planning that incorporates DSM with the objective functions of the environmental impact associated with the installed power capacity and energy output has been presented (Martins et al., 1996). A new mixed-integer programming-based structure for cost-and-emission-based maintenance scheduling incorporating with DR programmes has been suggested (Mollahassani-pour et al., 2015, Mollahassani-pour et al., 2017). The environmental impact of DSM and the potential environmental trade-off between system cost and power plant emission reductions have been discussed (Reddy and Parikh, 1997). The effect of a carbon tax and DSM programmes in the Indonesian power sector has been discussed from the perspective of long-term integrated resource planning (Feuerriegel et al., 2012)

The above discussion shows that DSM programmes can be integrated into the planning and operation of electrical power systems to mitigate environmental damage.

2.2.3 Power System Operation

The impact of DSM on power system operations is discussed from the following viewpoints:

2.2.3(a) Voltage Stability

Voltage stability is the ability of power systems to keep voltages within acceptable limits at all buses under normal functioning conditions and after disturbances (Kundur et al., 2004). The proven ability of DSM to help achieve voltage stability in power systems is important for alleviating transmission congestions that are otherwise limited by bus-voltage violations (Aghaei et al., 2016). The DR programmes, when implemented at appropriate buses, can improve voltage stability (Affonso et al., 2006, Aghaei et al., 2016, Hu et al., 2012, Choo et al., 2009, Hayes et al., 2010, Xu and Milanović, 2016, Soni and Panda, 2017, Hui et al., 2012, Husain et al., 2013), and small single stability (Hu et al., 2011) for both normal and outage operating conditions. On the other hand, DR can maintain frequency stability as well (Babahajiani et al., 2016).

2.2.3(b) Transmission Congestion

As the DSM seeks to flatten the load profile and reduce the duration of peak load periods, the required transmission capacity decreases, and this effect indirectly relieves transmission congestion (Kumar and Sekhar, 2012, Dehnavi and Abdi, 2017). Optimal power flow has been applied to maximise system benefits through the evaluation of the optimal allocation of demand-side resources (Hayes et al., 2014). Next, a procedure for determining the optimal busses for demand response has been developed on the basis of power transfer distribution factors, available transfer capability and dynamic DC optimal power flow (Dehnavi and Abdi, 2017). The multi-objective particle swarm optimization method has been used for transmission congestion management considering DR (Zaeim-Kohan et al., 2018).

2.2.3(c) Preventive Maintenance

Maintenance scheduled is divided into two parts, namely, preventive and corrective maintenance. Preventive maintenance is performed in order to keep the system in a condition that is consistent with the required levels of performance and reliability. While corrective maintenance is necessitated by system in-service failures or malfunction. Generating units are sporadically scheduled for preventive maintenance to reduce the risk of being out of service. During the scheduled outages, the unit is unavailable. Preventive maintenance is scheduled maintenance and is an outage that is managed and planned in advance; it is deferrable if necessary and includes component removal (Billinton, 2013). A scheduled outage is not commonly involved in the reliability evaluation. However, this does not refer that such outages do not happen practically (Billinton, 2013). Preventive maintenance must be performed when system components approach the end of their useful lifespan or when failures are anticipated (Allan, 1983). Preventive maintenance is periodically scheduled for generating units, transmission lines and distribution networks to reduce the risk of being out of service. Security-constrained preventive maintenance scheduling linked with DR programmes has been used to determine the optimal outage scheduling of generating units for minimising emissions and decreasing maintenance, fuel and reserve costs (Mollahassani-pour et al., 2017, Mollahassani-pour et al., 2015).

2.2.3(d) Facility Upgrade

The peak demand period occurs approximately 5% of the load cycle and consumes nearly 1% of the total system energy. Therefore, building new generating units to satisfy this need is uneconomical. Although DSM and peaking generating units can efficiently resolve this issue (Billinton and Huang, 2006), DSM programmes can postpone investments in new generation units (Martins et al., 1996, Pina, 2012, Pina et al., 2012) and the expansion of transmission and distribution networks (Hoff, 1996, Hajebrahimi et al., 2015). The role of DR programmes as an alternative solution to the required transmission upgrades have been explored (Vatani et al., 2018).

2.2.3(e) Renewable Energy Sources

Renewable energy sources (RES) are stochastic in nature, intermittent, unpredictable and uncontrollable. Despite this, they remain crucial sources for a sustainable future grid. DSM has been used aggressively as a method to mitigate the effects of RES intermittency by implementing various methods such as DLC and energy storage systems (ESS). However, they cannot be implemented in real-time like load scheduling (Soni and Panda, 2017). DSM is considered as a valuable tool to mitigate the intermittency of RES (Moura and De Almeida, 2010). Whereas DR programmes are able to mitigate the negative impacts of wind energy intermittency towards the reliability of the electrical power systems (Moshari et al., 2016). Many studies have assessed the intermittency of renewable energy sources either at the supply side as bulk units or at the demand-side as medium units. A priority-based DR and ESS for solar photovoltaic systems have been proposed to mitigate the intermittency of power generation (Kandasamy et al., 2017). DSM has been used to integrate the growing number of renewable energy sources in Portugal (Moura and De Almeida, 2010). A probabilistic programming for smart microgrids has been implemented by considering DR as compensation for the uncertainty caused by wind and solar power generation (Aghajani et al., 2017). The technical potential of active load management in a distributed electrical power systems with a high penetration of RES was studied in (Zong et al., 2012). The impacts of adding wind power and DR on both greenhouse gas emissions and generator cycling requirements has been proposed to show the effectiveness of DR in mitigating the variability of renewable generation (Broeer et al., 2018).

2.2.3(f) Power System Flexibility

DSM is an emerging flexible resource management strategy and exerts the dual impact of decreasing electricity demand and allowing efficient and flexible system management (Heydarian-Forushani et al., 2017, Pina et al., 2012, Bergaentzlé et al., 2014). Power systems with highly mixed renewable energy sources are less likely to meet consumer demands than conventional systems with only fossil-fuel generators. Although this condition rarely occurs because of the ancillary services provided by energy storage systems, the financial implications of an electricity outage and possible blackout cascade are too massive to be ignored. In this context, DSM can be extremely valuable because it decreases electricity consumption during times of peak