The Institution of Engineering and Technology

# Emerging Capability on Power System Modelling: System Security, Resilience and Recovery Modelling

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# About this report

The Institution of Engineering and Technology was commissioned by the Council of Science and Technology (CST) to research the emerging challenges for modelling electricity systems and how Britain's capabilities would need to be adapted to assess electricity system resilience as GB makes the transition to a low carbon electricity system.

This project commissioned, and received, fifteen individual papers from GB-based specialists of international standing in power system modelling. The authors of the papers worked with a wide stakeholder base of network companies, academics and others, who provided review and challenge. Professor Graham Ault CEng FIET was contracted to provide technical co-ordination and drafting. The emerging conclusions were further validated by means of an industry and academic workshop sponsored by Government Office for Science. The entire project was conducted under the direction of an independent steering committee composed of senior IET Fellows, two of whom were also CST nominees.

**The report is composed of three parts:**

- Part 1: Main report
- Part 2: Summary of Commissioned Papers
- Part 3: IET Special Interest Publication – Academic & Industry Papers

All three parts of this report are available from the IET website at:

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## EXECUTIVE SUMMARY

According to the IET power network joint vision report [1], significant changes are needed across the nation's power networks to facilitate a 'one system' approach. It has been recognised that decarbonisation of energy supply is considered to be the biggest even change to GB's national energy infrastructure being created with two-way power flows (in particular for distribution grids), less predictable distributed generation and demands (including massive EV charging) and large scale intermittent wind energy generation, in particular. In this situation, the requirements for network operators (both for transmission and distribution grids) are huge to ensure the reliability, security and resilience of power grids in terms of a shock, either big or small.

One of the big challenges is to develop robust recovery strategies to bring the system back to normal status in case of big disturbance to the power grid. The problem of bulk power system recovery following a complete or partial collapse is actually as old as the electricity industry itself. Many electricity industry companies have developed methods, tools and procedures to cope with the system recovery issues. However, it is necessary to review the existing methods, tools and procedures and understand the challenges ahead and hence it is absolutely useful to understand the gaps for the development of new recovery methods and tools under the new environments with massive distributed energy sources and smart grid controls.

This report reviews the current operating practices, conducts a literature search, prepares relevant bibliographies, and understands the current modelling capability for power grid security, resilience and recovery, and discusses the emerging phenomena and modelling requirements. Finally we will provide recommendations in terms of the technical gaps in power grid security, resilience and recovery modelling.

## 1. BACKGROUND

The commercial use of electricity began in the late 1870s when the inventive genius of Edison brought forth the electric incandescent light bulb. The first complete electric power system – The Pearl street system in New York began operation in 1882, which was actually a DC system with a steam driven DC generator. With the development of the transformer, polyphase systems and AC transmission, the first three-phase line in North America was put into operation in 1893. It was found that AC transmission with the help of transformers was more preferable since DC transmission became impractical due to higher power losses at that time.

With the development of electric power systems, interconnection of neighbouring electric power systems leads to improved system security and economy. However, with the advent of interconnection of large scale power systems, operation, control and planning of such systems become challenging tasks. With the advent of interconnected large scale electric power systems, new dynamic phenomena including transient stability, voltage stability, low-frequency oscillations etc have emerged. With the development of electricity market, electricity companies engage in as many transactions in one hour as they used to conduct in an entire day. Such increased load demand along with uncertainty of transactions will further strain electric power systems. Moreover large amounts of decentralized renewable generation, in particular wind generation, connected with the network will result in further uncertainty of load and power flow distribution and impose additional strain on electric power systems operation and control. It is a real challenge to ensure that the transmission system is flexible enough to meet new and less predictable supply and demand conditions in competitive electricity markets.

FACTS devices and HVDC links are considered as low-environmental-impact technologies and are a proven enabling solution for rapidly enhancing reliability and upgrading transmission capacity on a long-term cost-effective basis. The ever-increasing frequency of blackouts (see Table 1) seen in developed countries has also enhanced the need for new power system control technologies such as FACTS devices and HVDC links. With the developments of advanced technologies and operation concepts such as FACTS, HVDC, Wide Area Measurements, Microgrid systems, and smart metering, demand side management, energy storage as well as likely massive deployment of Electric Vehicles, the developments in smart grids are underway.

Power blackouts are referred to as very large scale long duration interruptions. Although blackouts are considered to be rare events, the impacts of these events are quite often very significant. Table 1 overleaf shows the major worldwide power blackouts as well as the economic losses when data is available.

Following a power blackout or an interruption, power supply needs to be recovered as quickly as possible in order to minimise the economic losses. In fact, power system recovery is not completely new. The problem of bulk power system recovery following a complete or partial collapse is actually as old as the electricity industry itself. Many electricity industry companies have developed methods, tools and procedures to cope with the system recovery issues. However, it is necessary to review the existing methods, tools and procedures and understand the challenges ahead and hence it is absolutely useful to develop these further under the new environments.

## MAJOR POWER BLACKOUTS:

**February 8-9, 2013:** some 650,000 homes and businesses in the north-eastern US lost power as the result of a powerful nor'easter that brought hurricane-force wind gusts and more than two feet of snow to New England.

**October 29–30, 2012:** Hurricane Sandy brought high winds and coastal flooding to a large portion of the eastern United States, leaving an estimated 8 million customers without power. It is virtually impossible to protect the system from a storm like Sandy.

**July 31, 2012:** Three power grids across half of India fail in what authorities call overdrawing of the system. The blackout was the largest power outage in history, occurring as two separate events on 30 and 31 July 2012. The outage affected over 620 million people, about 9% of the world population, or half of India's population, spread across 22 states in Northern, Eastern, and Northeast India. An estimated 32 gigawatts of generating capacity was taken offline in the outage. Electrical power was restored in the affected locations between 31 July and 1 August 2012.

**Feb 4, 2011:** Brazil (at least 8 states in north-eastern: Alagoas, Bahia, Ceará, Paraíba, Pernambuco, Piaui, Rio Grande do Norte and Sergipe) Technical failure, a failure in an electronic component that was part of protection system of the concerned substation. The blackout lasted about 16h while 53m people were affected.

**Nov. 10, 2009:** Brazil (most states) + Paraguay. Storms near the Itaipu hydroelectric dam on the Paraguay-Brazil border are blamed for power cuts to as many as 87 million people in Brazil for 25min to 7h. The entire nation of Paraguay, population 7 million, was also briefly blacked out. Natural event, heavy rains and strong winds caused three transformers on a key high voltage transmission line to short circuit, cutting the line and automatically causing all of the hydroelectric power plant's 20 turbines to shut-down due the abrupt fall of power demand (the world's second largest hydroelectric dam).

**January-February 2008:** Winter storms cause a nearly two-week blackout to about 4 million people around the central Chinese City of Chenzhou. Eleven technicians reportedly die trying to restore power.

**November 4, 2006:** South West Europe (parts of Germany, France, Italy, Belgium, Spain and Portugal). A German power company switches off a high voltage line over a river to let a cruise ship pass. It triggers outages for 15 million people in Germany, France, Italy and Spain.

**August 18, 2005:** Indonesia (Java Island). Due to the technical failure, power failed along the electrical system that connects Java, Bali, and Madura, causing outages in Java and Bali. This led to a cascading failure that shut down two units of the Paiton plant in East Java and six units of the Suralaya plant in West Java. It lasted 7h while 100 million people were affected.

**Nov 29, 2004:** Spain. Human error/technical failure, overloaded transmission line. 5 blackouts took place within 10 days and 2 million people were affected.

**Sept. 28, 2003:** Italy (all Italy, except Sardinia). A short in a power line in Switzerland leads to blackouts affecting 95% of Italy. Some 55 million people were without power for as long as 18 hours.

**Aug. 14, 2003:** The worst US blackout. Power line problems in the Midwest trigger a cascade of breakdowns that cut power to 50 million people in eight states and Canada, some for more than a day. The total economic loss was estimated about USD 6 bn.

**January 2, 2001:** India. The blackout was due to the technical failure of substation in Uttar Pradesh. The12h blackout affected some 226 million people while the economic loss was estimated to be US$ 110m.

**Feb 20, 1998:** New Zealand. Due to the technical failure, a chain reaction caused by a line failure. It lasted for 4 weeks while 70,000 people were affected.

**July 13, 1977:** A lightning bolt knocks out electricity to about 8 million people in New York City. Power isn't fully restored until 25 hours later after widespread looting.

**Nov. 9, 1965:** The Great Blackout left the power out for 25 million people in New York.

## 2. METHOD

System recovery is a strategic issue for ensuring the reliability and security of power grids and minimising the interruptions to market operations, which has attracted continuous attention from industry, academia and governments. There are a large number of papers and reports available. The objectives of this brief paper are to:

- give a brief review of the worldwide existing practices
- understand the market aspects of system recovery
- present the existing tools for system recovery being used
- address the emerging methods and facilities for system recovery
- identify the modelling gaps for better system recovery strategies and procedure to deliver a secure and resilient UK electricity grid.

In this brief paper, we have adopted the basic concepts proposed in [2, 3, 4] where the operating states of a system are classified into four categories, namely, normal state, alert state, emergency state and restoration state. The conceptual diagram describing the relationship between the four operating states is shown in Figure 1.

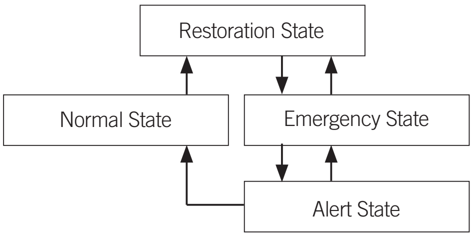


**Figure 1: System operating states.**

***Normal operating state:*** In the normal operating state, all constraints such as voltage and thermal limits are satisfied, the total generation is adequate to supply the total load demand, no equipment is overloaded. In this state, reserve margins (for both transmission and generation) are sufficient to provide an adequate level of security with respect to the stresses to which the system may be subjected.

Typical control functions at this state include:

- Monitoring and estimation of the load and generation
- Static state estimation
- Monitoring of the system loading conditions and security
- Balancing generation and demand
- Regulating frequency
- Demand side management.

***Alert operating state:*** If the security level falls below the given threshold of adequacy, or if the probability of disturbance increases, then the system enters the alert state. In this state, all constraints are still to be satisfied, but existing reserve margins would be such that some disturbance could result in a violation of some inequality constraints; e.g., equipment would be overloaded more or less severely above its rated capabilities. In this alert state, preventive actions can be taken to restore the system to the normal state and the possible control actions include:

- Adjusting network power flows and voltage profiles
- Modifying tie-line power transfer schedules
- Bring on new generation if needed

***Emergency operating state:*** If a sufficiently severe disturbance takes place before a preventive action can be taken, the system enters the emergency state. Here, inequality constraints are violated, and system security would have been breached since the "security level" would be below zero and practically non-existent. The system, however, would still be intact, and 'emergency' control action could be initiated in order to restore the system to at least the alert state. Once a system has entered the emergency state, the deliberate control decisions and actions that are appropriate to the normal, and even the alert, state are no longer adequate, and more immediate action may be called for.

The objective of the emergency control is to relieve the system distress and satisfy a maximum power supply to customer demand. The emergency controls include:

- immediate control to clear equipment overloads
- fault clearing
- fast valving
- dynamic braking
- exciter control
- HVDC modulation
- load control
- capacitor switching
- controlled islanding
- plus all controls mentioned in the alert state.

***Restorative operating state:*** If these measures are not taken in time, or are ineffective, and if the initiating disturbance or a subsequent one is severe enough to overstress the system, the system then starts to disintegrate. In this state, both equality and inequality constraints have been violated; the system would no longer be intact where major portions of the system load would be lost. Usually this is the aftermath of an emergency operating state.

The control objective of restorative operating state is to take appropriate control actions to bring the system from partial to full satisfaction of all customer demands in minimum time.

The restorative controls include:

- unit black-starting/restarting and/or synchronization
- black-starting of HVDC links
- load restoration
- synchronization of control area.

The system recovery covers both the emergency and restorative operating states and associated controls. In the next sections, we will discuss the current practices of system recovery in the global point of views, summarise the existing simulation and modelling capability in Europe and in particular in the UK. New environments will be outlined, and then emerging technologies will be presented and it will be discussed how these factors will have impacts on the future needs of simulation tools for system recovery.

# 3. CURRENT POWER SYSTEM MODELLING CAPABILITY FOR SYSTEM RECOVERY

## 3.1 Current Practice of System Recovery

We will review the current practices of system recovery including emergency control and restoration. The review will cover mainly the practices of Europe (ENTSO-E), North America and emerging countries such as Brazil and China. The topic areas include system defence plan and system restoration.

### 3.1.1. System defence plan

#### ENTSO-E

Defence plans normally consist of a set of coordinated measures, which provide generic technical recommendations and rules for manual and automatic control actions to manage critical system conditions to prevent the system from the loss of stability and cascading effects leading to major blackouts. The major purpose of the defence plans is to maintain the integrity of the interconnected system in case of extreme contingencies.

The defence plans for the case of ENTSO-E include the inter actions between TSOs and actions taken by an individual TSO. As far as interactions are concerned, each TSO is expected to operate their own system while not to cause problems to their neighbouring systems.

Typically a fault on a system shall not cause serious operational disturbances in other neighbouring systems. On the other hand, neighbouring TSOs shall provide maximal assistance to support the TSO with the disturbance. All the relevant TSOs shall take all possible internal and coordinated measures to take appropriate actions to relieve the constraint due to the disturbance.

The tie lines between TSOs are considered as the backbone of the interconnected system and disconnection from the interconnected system with opening of tie lines should be considered to be the remedial action of last resort with coordination with the neighbouring TSOs. For instance, in the Great Britain and in the Ireland/Northern Ireland areas, emergency assistance protocols are available for HVDC interconnectors. Similar protocols are available in the Nordic area. These protocols include manual regulation actions and automatic functions for instance, emergency power control and frequency control.

Normally a frequency deviation from the nominal frequency due to an imbalance between generation and demand occurs continually during normal system operation or after an incident. There are different frequency ranges for normal operation in different Synchronous Areas within ENTSO-E. For the Baltic system synchronously working with IPS/UPS (Russia, Ukraine, etc) system, operational limit for frequency is 50.00 ± 0.05 Hz. Frequency deviation of 50.0 ± 0.2 Hz needs to be brought back to the normal operational limit within 15 minutes. In the Continental Europe area, absolute frequency deviation should be within the maximum deviation of 0.2 Hz. In the Great Britain area, the normal operational limit for high frequency is 50.0 ± 0.2 Hz. The statutory limits from the Security & Quality of Supply Standards are 50.0 ± 0.5 Hz. In the Ireland/Northern Ireland area, the operational limit for frequency is very similar to that in the UK. In the Nordic area, the normal operating range is 50.0 ± 0.1 Hz. In addition, for different TSOs, they have different control measures for the management of high frequency and low frequency deviations. More detailed description can be found in [5].

Current practices for under frequency load shedding (UFLS) include [5]:

- TSOs coordinate with DSOs to regularly check the load shedding plan in order to ensure the predicted load shedding when applied.
- TSOs implement load shedding in an evenly distributed way.

- TSOs implement a UFLS plan that avoids disconnecting feeders with connected dispersed generation.

Requirements for equipment in case of frequency deviation are different in every synchronous area and usually there are differences between countries. The amount of load to be disconnected is determined by the warning issued by the TSO, while the DSOs are obliged to carry out the load shedding required.

Normally system defence plans shall include critical voltage levels and all reactive power compensation capabilities. Remedies via automatically or manually controlled reactive power compensation are taken to keep voltages between critical limits. In order to prevent voltage collapse, in a defence plan, the following control actions should be taken by TSOs to [5]:

- block the transformer tap changers
- reduce load by reducing voltage on the secondary side of transformers (typically -5% Un)
- use UVLS relays at certain points on the network
- provide manual load shedding
- provide special measures including lowering of active power output of units to widen available reactive power range (according to the PQ diagram)
- automatically disconnect shunt reactances in case of low voltage
- provide emergency power control of HVDC
- instruct simultaneous tapping of generator transformers.

Specific grid user needs should be considered in defence plan, for instance, civil safety (including nuclear safety) is of highest importance, and hence TSO defence plans should ensure power supplies to nuclear power plants and maintain power supplies to national strategic facilities, e.g. hospitals, power plants, airports and factories with potential environmental impacts, gas pumping station etc.

In terms of emergency situations, TSOs have the possibility to interrupt or, in cooperation with power exchanges, stop the Day-ahead and Intraday markets. For instance, in Great Britain, with a total or partial shutdown, the TSO will inform Users and the Balancing Settlement Code Company that the TSO intends to implement a Black Start. In Nordic and Baltic system, the day ahead and intraday markets are operated normally as long as possible. In case of unexpectedly reduced power flows due to tripping of a line for example, all trades carried out in the markets will remain valid, if necessary, the TSOs will need to reduce cross border flows. In Ireland and Northern Ireland, the market is settled ex-post and there are specific rules for settlement in the event of Black Start.

#### State Grid Corporation of China

The stability criteria in China are classified into 3 levels according to the contingency severity [7]:

- ***Defence Level 1:*** For a plain contingency such as a single-phase short-circuit, all loads should be kept by applying only the first defence-line. Preventive control reschedules the generation and shifts the operating point into the stability domain.
- ***Defence Level 2:*** For a severe contingency such as a three-phase short circuit, the system integrity should be kept with regional emergency control.
- ***Defence Level 3:*** For an extremely severe contingency, such as multi short-circuits occurring concurrently, system-wide blackout should be avoided by activating local emergency control.

The three defence-lines have successfully prevented system-wide blackouts in China. The simulation tool is supported by a very fast transient stability programme.

#### Brazil

Operative Security Control Actions for the National Grid System include:

- Preventive control actions to minimize the probability of occurrence of large disturbances.
- Corrective control actions to minimize the spreading of unavoidable disturbances through the system.
- Optimized restoration actions: to reduce the restoration time to acceptable values.
- Disturbances analysis to identify eventual problems to avoid the occurrence of new blackouts or minimizing their consequences.

### 3.1.2 System restoration

#### Europe (ENTSO-E)

In ENTSO-E, restoration plans consist of a set of control actions implemented after a disturbance to bring the system from emergency or blackout system state back to normal state. Restoration actions are initiated when the system becomes stable following the implementation of the system defence plan. Restoration of the system is obtained via a sequence of coordinated control actions. Restoration plans need to consider available resources of generators and HVDC links in the TSO's area.

TSOs need to coordinate the following control actions for the restoration of system:

- Re-energisation strategy after a blackout is based on two approaches, namely, Bottom-up approach (GB) and Top-down approach (Baltic area) **[5]**, while in the Continental Europe and the Nordic areas, both approaches are used. In all areas, the reconnection of generators tripped due to abnormal frequency excursion and of shed load should be coordinated by TSOs.
- Emergency frequency restoration processes start after a severe disturbance with a frequency deviation higher than the maximum permissible or in case of system split.
- For split situations, a re-synchronisation has to be initiated, after emergency frequency restoration.
- Market restoration.

In the case of restoration the DSOs shall restore load according to TSOs instructions with respect to restoration plans. DSOs have to provide the TSO with all the necessary information such as:

- Generator island operation capability.
- Generator house load operation capability.
- Black Start units.
- HVDC Black Start capabilities.

Basically restoration plans should be tested in advance by simulations. Some TSOs perform real tests besides simulations. Neighbouring TSOs will need to prepare and agree in writing bilateral agreements on system restoration principles and procedures. In restoration plans, priorities should be given to specific grid users, e.g. hospitals, emergency services, airports, etc. Market restoration can only be achieved after the restoration of the system.

**PJM**

In the USA, the aim of the PJM system restoration plan is to restore the integrity of the interconnection as quickly as possible, via the following steps taken by PJM, Transmission Owners and Generation Operators **[6]**:

- Performing a system assessment to determine extent of outage.
- Starting Black Start units to form islands.
- Building cranking paths to other generating units, nuclear stations and critical gas facilities.
- Restoring critical load.
- Synchronizing and interconnecting islands to form larger islands.

- Connecting to outside areas.
- Returning to normal operations.

Minimum objectives of restoration plans are to:

- Provide nuclear stations with auxiliary power to maintain safe shutdown within 4 hours.
- Restore interconnections between all internal TOs.
- Restore interconnections to all external Reliability Coordinator Areas.

Very similar to general operating principles in ENTSO-E, when a system disturbance occurs, it is important to:

- maintain an interconnected operation throughout the PJM Regional Transmission Operator (RTO) and the adjacent interconnected Balancing Authorities.
- provide maximum assistance to the other Balancing Authorities in order to prevent cascading failure to other parts of the interconnected system and assist in restoration of normal operation.

Depending on the level of the disturbance and available resources post-disturbance, PJM may implement a "Top-down", "Bottom-up", or both a "Top-down" and "Bottom-up" restoration strategy simultaneously to restore the system as quickly as possible.

In general, a system restoration plan includes the following:

- Ascertaining System Status
- Determining Restoration Process
- Disseminating System Status Information
- Implementing Restoration Process
- Frequency Control
- Verify Switching Equipment Constraints.

### Brazil

Restoration started from high reliability (black start) hydro-power units and the maximum amount of power in each priority load pick up for each geo-electrical area must be pre-defined. The National and Regional Operating Centres shall coordinate the load shedding and closing of loops or parallel indistinct geo-electrical areas. Restoration time can be reduced by taking the following actions [8]:

- Improvements in off-line studies.
- Elaboration of more detailed and precise operation instructions.
- Identification of new resources for the energisation procedure.
- Operators training.
- Feedback from disturbances analysis.

### 3.2 Current Simulation Tools

In this brief paper, we will review the different simulation models and tools available and hence understand the existing simulation capability.

Power system restoration [11] analytical tools include a set of off-line and on-line programs which together describe the static, transient and dynamic behaviour of a power system during restoration [10]. The tools are summarised as follows [9]:

- ***Power Flow (PF) Program:*** Sustained overvoltage control; Reactive power balance; Line and transformer thermal limits
- ***Transient Stability (TS) Program:*** Subsystem stability; under-frequency load shedding; Low frequency isolation scheme; Intentional islanding
- ***Long-Term Dynamic (LD) Program*** [40]***:*** Frequency response of prime moves; Response reserve; Load frequency control
- ***Voltage Transient (VT) Program:*** Switching surges; Insulation coordination
- ***Short Circuit (SC) Program:*** Minimum source currents; Breaker interruption ratings; Relay coordination
- ***Electromagnetic Transient Program (EMTP):*** Insulation coordination and switching surge; Harmonic resonance and ferro-resonance, SSR, and Magnetizing transformer inrush over-voltages
- ***Standing Phase Angle (SPA) Program***
- ***Cold Load Pickup (CL) Program:*** Heuristic approach; Physical modelling
- ***Restoration Coordination Program (CPM):*** Allocation of resources; Scheduling of restoration tasks; Estimation of restoration duration; Evaluation of restoration process

System operators can gain the necessary experience to confidently deal with time-critical restoration problems, through training. [33] and [34] give a general overview of operator training techniques for power system restoration. The Operator Training Simulators (OTS) have been developed to verify restoration plans [30, 31, 32, 35, 37].

Over the years, advanced simulation techniques for extended power system dynamics [38] have been developed.

[41] Presented the techniques of dynamic simulation of large scale system using the Extended Term Simulation option of the Power System Simulation Program (PSS/E) which can consider both fast and slow dynamics with dynamically changing step-size for the integration.

An efficient, numerically stable solution algorithm for large-scale power system dynamic simulation over a wide dynamic range has been described. This algorithm, based on simultaneous solution of the differential-algebraic power system equations using a modified trapezoidal method, has a number of advantages [42].

Advanced variable step size algorithm has been developed in EUROSTAG [43] [44]. The algorithm has been developed further for real-time simulation of pan European grid recently [30].

In [39], multiple timescale properties for fast simulation algorithms have been exploited in DigSILENT where adaptive step size algorithms were presented to use the multiple time scale characteristics of power systems. The paper analyzed methods using multiple step sizes simultaneously (multi-rate methods) and methods adapting the integration step size in time. The resulting algorithm covers transients of all time ranges, from electromagnetic to electromechanical phenomena.

# 4. EVALUATION OF MODELLING CAPABILITY AND GAPS FOR SYSTEM RECOVERY

## 4.1 Emerging Technologies

### 4.1.1 FACTS devices [25, 26, 27]

FACTS can bring the potential benefits to system restoration [45]. However, they will also bring technical difficulties with the firing controls of thyristor based FACTS devices due to system frequency fluctuations associated with the load pick-up in the initial restoration phase. Apparently, the present practice is to switch-off the SVCs devices during power system restoration due to some reasons including voltage regulator loop instability during minimum source conditions.

The challenge of STATCOMs in restoration is to survive the presence of negative sequence currents and large voltage dips due to their inability.

### 4.1.2 HVDC links/Blackstart [22, 23, 24]

From [13], it can be seen that the recovery from disturbances depends on the system, the individual controls need to be tuned, based on simulations, to provide the best compromise of mutual performance. The strategy provided staggered recovery through a variable timed modification to the rectifier current reference produced the best overall performance.

Although LLC HVDC does not have the black start capability, VSC HVDC does have the black start capability. In [19], the new black start: system restoration with help from voltage-sourced converters was illustrated with real life examples.

### 4.1.3 Energy storage

Our vision is that there will be technical and economic benefits of energy storage for competitive and regulated markets, and for different applications and regions [46]. Energy storage will improve grid reliability, facilitate system resiliency/energy security, and deliver national policy objectives [14, 21]. Energy would be largely beneficial to the system recovery.

### 4.1.4 Demand response for frequency restoration

In [15], the emergency demand response was introduced to cope with the spinning reserve for realizing an adaptive frequency restoration plan. It is expected such a scheme would play an important role in frequency restoration in future [20].

### 4.1.5 Electric vehicles

It was suggested in [18], EVs at micro-grid level can be exploited to support a local restoration procedure following a blackout to take advantage using their storage capacity and charging flexibility.

### 4.1.6 PMU and wide area monitoring

In [47], PMUs have been used in restoration planning with improved observability. In addition, PMU can provide remote feedback control signals for damping system oscillations. In [48], power system stability assessment during restoration based on a wide area measurement system has been presented. In [16] a wide area monitoring system based load restoration method has been proposed. With the real-time system status gathered by WAMS, it is easier for system operators to implement the load restoration plan with the guaranteed power system stability.

## 4.2 Needs for New Simulation Tools for System Recovery

### 4.2.1 Needs for new massive simulation tools

A time recovery process would cover a full spectrum of power system phenomena from fast power system control to slow power system control, and from fast dynamics to slow dynamics as shown in Figure 2.

Restoration challenges can be subdivided into three areas: regulatory, economic, and technical. Restoration plan and procedures need to be tested. One of the best testing approaches is studied via suitable simulation tools. Due to complexity of couplings between regulatory, economic, and technical aspects, the current DTS or OTS could not provide such comprehensive simulation functions. There are needs also that consider emerging technologies such as FACTS, HVDC, demand side response, PMU & wide area monitoring and control as well as energy storage.

The development, testing, and deployment of future smart grids will be accelerated by the availability of massive real-time open architecture simulators and massive real-time simulation events can be conducted to simulate large-scale interconnection-wide disturbances while providing realistic experiences to large numbers of participants [29], and the purposes of massive real-time power system simulator can be used to:

- train power system operators;
- test smart grid wide area visualization methods;
- test smart grid emergency load control methods;
- test self-healing smart grid controllers;
- test smart grid maximal flow remedial action controllers;
- test smart grid islanding methods;
- test market pricing methods to stimulate demand response;
- and distributed energy resource production;
- test the relationship between future system regulatory policies, market designs, and smart grid technologies.

A significant step towards massive real-time simulation can be used for training system operators and power engineers to conduct large-scale restoration drills using a custom simulator. However, the first generation of operator training simulators has been built on long-term dynamic simulation models where dynamic equations of boiler-turbine-governors, hydro penstock-turbine-governor systems, automatic generation control systems, island frequency response, and transformer tap changer response are normally considered.

The long term dynamic models [36] are accurate enough for power system power/frequency response calculations. Such models may not be justified for future resilient power grids with a lot of smart/power electronic controls. It is expected that EMT type simulations are needed with short term dynamic phenomena. It has been pointed out in [12] that most of the restoration studies, only steady-state and stability cases are considered, nonetheless all of the restorations in Brazil have shown the necessity of incorporating electromagnetic transients studies; otherwise, unrealistic results may occur leading to an inefficient and risky restoration process as is the case of the Rio de Janeiro Area presented here. It is concluded that for a system where the transmission distance is high, over 400 km, there must be a careful analysis of the performance concerning not only steady-state and stability but also electromagnetic transient studies.

### 4.2.2 Emerging simulation capability and future possibilities

With the recent advances in high performance computing technologies, a massive parallel processing computer can solve the Power System transient stability of the USA WECC 16351-bus (RMS) simulation of 30s faster than real-time. The integration step-size is 10ms. The near future target is to solve a system up to 20,000-bus faster than real-time. Using today's cheaper multi-core computer, a power system with some 10,000-bus can be solved faster than real-time.

China EPRI has developed the ADPSS which simulates a system with 1000 machines and 10,000 buses using 16-node PC Cluster. ADPSS can consider electro-mechanical transients or mixed electromagnetic/electro-mechanical transients. China Southern Power Grid can use their RTDS to simulate their system with all the buses of 220 kV and above with the detailed electromagnetic transients.

However, for EMT type simulation, the maximum system being solved is much smaller than that for RMS type simulation. In the foreseeable future, with further R&D work, it would be possible to solve a system up to 10,000 buses on real-time basis.

Consider a UK national real-time energy system simulator for testing smart grid control strategies, a fundamental design building upon the advanced technologies is needed.

The simulator is expected to have the following distinguished features:

- it should be able to simulate both EMT type phenomena but also RMS type phenomena on real-time basis.
- it should be able to simulate basic functionalities of control centres.
- it should be able to simulate the power system dynamics but also the dynamics of market operations [28].
- it should be able to simulate the whole energy system and hence would allow the studies of interactions between different energy supply systems if needed.
- it should allow to interface with real-life data.
- it should be able to develop and validate defence plan against extreme weather events affecting electrical power grids [17].

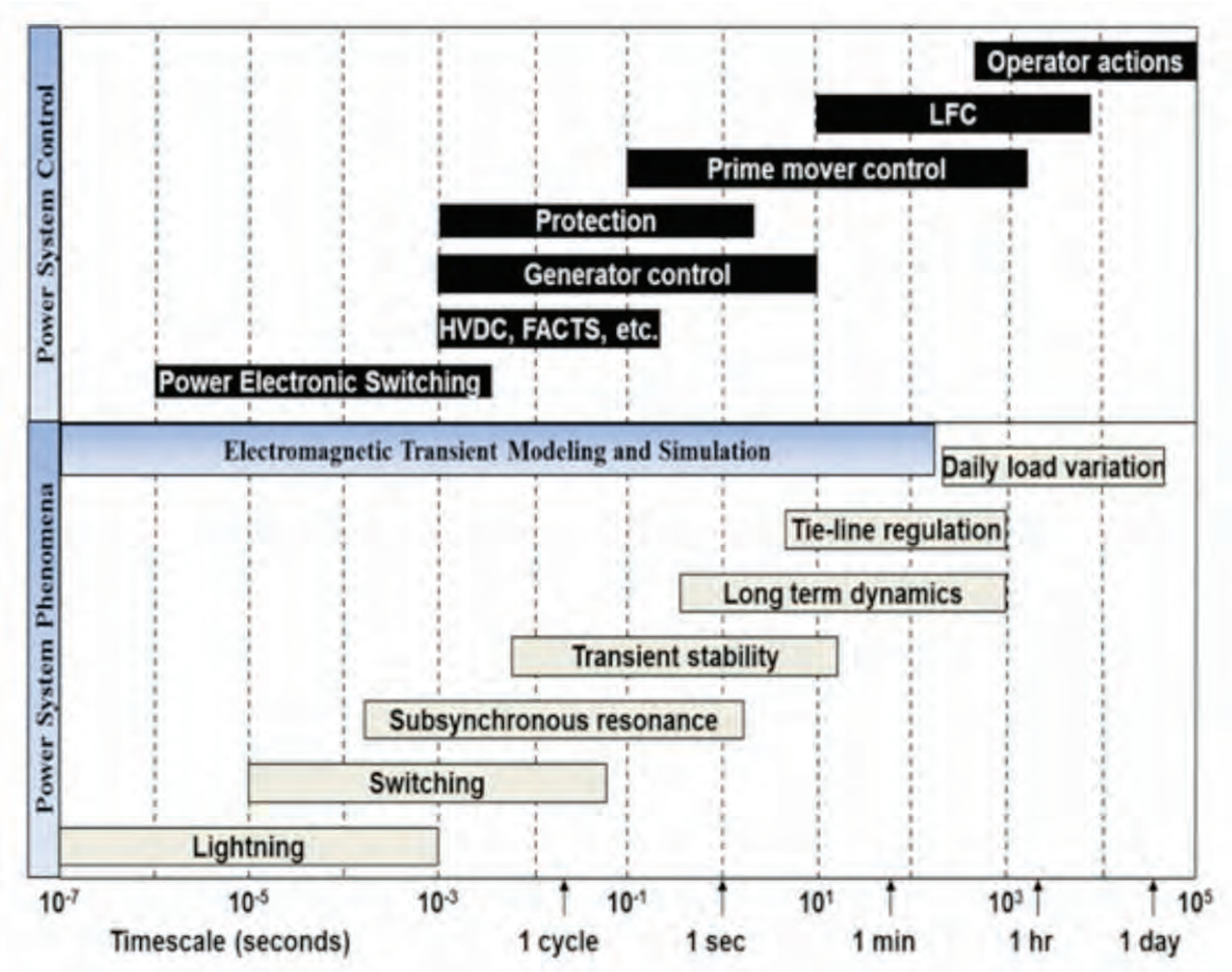


Figure 2: Time Frame of Power System Recovery.

## 5. CONCLUSIONS AND RECOMMENDATIONS

### Major issues of current simulation tools

1. Current simulation tools for system recovery largely rely on power flow algorithms or extended power flow algorithms (simplified stability simulation algorithms), which are neither adequate nor versatile.
2. Current power grid modelling and simulation efforts are often piecemeal, usually focusing on a narrow set of issues. The recent report by the IET has indicated that we will need to begin to address broader issues; the scope of such modelling and simulation efforts has yet to address national concerns.

### Near term objectives (next 1-3 years)

1. Development of real-time simulators for 10,000-bus system of RMS type phenomena and 1000-bus system of EMT type phenomena.
2. The system would provide, for instance, a high-fidelity simulation environment for testing new models and evaluating the grid system's performance.
3. Identification of risk scenarios such as automatic control system failure and loss of communications, cyber security attacks, etc.
4. Investigation of smart recovery strategies using distributed resources such as EVs and Energy Storage, and the impacts of heat pumps on the system recovery.
5. Dynamic power islands with distribute resources, smart controls and energy storage.

### Mid-term objectives (next 3-5 years)

1. The simulator should have very powerful interfacing capabilities to support wide area measurement based applications, power electronic applications including FACTS and other power electronic converters, and complex protection systems.
2. The simulator should provide full featured simulation capability over different phenomena as shown in Figure 2.
3. The system would provide functionalities of market operations.

### Long-term objectives (next 5-8 years)

1. A whole energy system with real-time simulation capability: A next generation national power grid simulator should focus on UK electric power grid modelling and simulation in the contexts of whole energy system approach, which will have connections with other critical infrastructures, such as transportation, oil and natural gas, water supply, and communications.
2. The system would provide functionalities of market operations.
3. Such a capability would provide a simulation framework and suite of integrated simulation tools to support needs for security, reliability, and resiliency as well as market operations of the UK national power grids.
4. The simulator should provide the opportunities to understand the operating challenges otherwise these would not be recognised easily.

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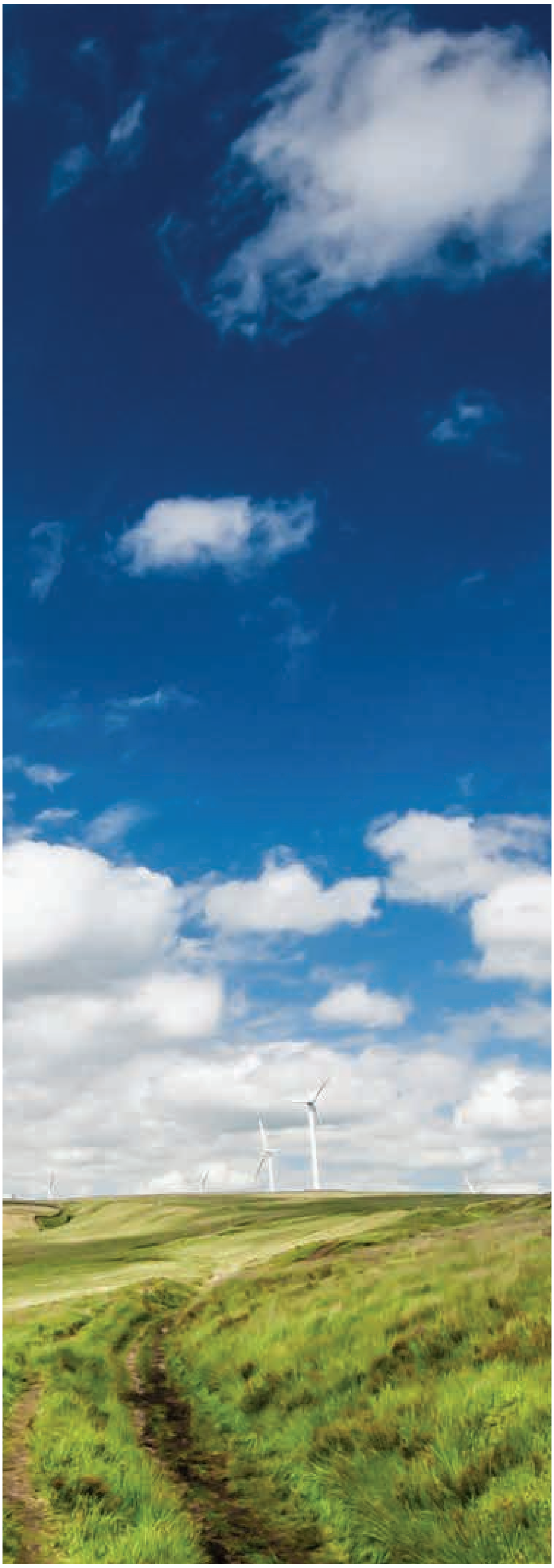

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