APPLICATION OF KINETIC ENERGY STORAGE SYSTEMS TO POWER SYSTEMS OPERATION

by

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To Rasha with love,

Abstract

This thesis analyzes some potential applications of kinetic energy (KE) storage systems in power systems operation. The goal was to take advantage of the KE stored in the existing rotating machines in a power system such as synchronous generators and motors by "borrowing" some of the stored KE when electricity prices are high and "returning" this energy to the rotating masses when the prices are down. As shown in this thesis, this operation can be performed from the control center by optimally scheduling the set points of the generators under automatic generation control (AGC) over a given time horizon. This coordination of KE was also tested with other types of rotating machines, namely synchronous and asynchronous flywheels.

The specific impact of this optimum coordination of KE storage has been tested from the perspective of power systems economics and security by investigating the method's potential to reduce the marginal price of electricity and to alleviate network congestion. In addition, this thesis examines the potential of KE storage systems to produce fast (10-30 second) reserve to be used during primary frequency regulation following the forced outage of a generating unit.

Résumé

Ce mémoire examine le potentiel des systèmes de stockage d'énergie cinétique appliqués à l'opération des réseaux électriques. Le but premier de ces systèmes est de profiter de l'énergie cinétique déjà emmagasinée dans les machines tournantes branchées au réseau. Avec ce mécanisme il s'agit d'utiliser une partie de cette énergie lorsque les prix de l'électricité sont élevés et de la retourner aux machines synchrones lorsque les prix redeviennent plus bas. Il est démontré que ce type d'opération est possible si le centre de commande du réseau établit l'ordonnancement des valeurs de consigne de la régulation automatique de la production des générateurs de manière optimale sur un horizon de temps donné. Ce schème de coordination de l'utilisation de l'énergie cinétique a été aussi examiné lorsque des volants d'inertie synchrones et asynchrones sont branchés au réseau.

L'impact spécifique de ce schème de coordination optimale du stockage de l'énergie cinétique a été évalué selon des critères économiques et de fiabilité en étudiant le potentiel de cette méthode dans la réduction des prix et la diminution de la congestion du réseau. De plus, une analyse des systèmes de stockage d'énergie cinétique comme sources de réserve tournante rapide (10-30 secondes) est effectuée. Pour cette application, les systèmes de stockage sont utilisés comme sources de réglage primaire de la fréquence subséquent à une indisponibilité fortuite d'un générateur.

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I wish to express my sincere gratitude to Prof. F.D. Galiana for his expert guidance; enthusiasm and continuous encouragement as well as his warm and friendly disposition, which were a source of motivation. It has been a privilege and honor to work under his supervision.

Some people might think
That teaching is just a chore,
A job that pays a salary,
Nothing less, nothing more,

But there is a special teacher,
Who has gone that extra mile,
Making it a passion, a prophecy,
With a welcoming heartfelt smile.

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Table of contents

- Abstract iii
- Résumé iv
- Acknowledgements v
- Table of contents vi
- List of symbols viii
- List of abbreviations x
- List of figures xi
- List of tables xiii

Chapter I. Introduction and Background 1

1.1 Introduction 1
1.2 Scope of Thesis 2
1.3 Background 3
1.3.1 Power Flow 3
1.3.2 Load Frequency Control 4
1.3.3 Economic Dispatch 5
1.3.4 Optimal Power Flow 6
1.3.5 Energy Storage Technologies 8
1.4 Thesis outline 9
1.4.1 Chapter 2 9
1.4.2 Chapter 3 10
1.4.3 Chapter 4 10

Chapter 2. Theoretical Development 11

2.1 Device Models 15
2.1.1 Load 15
2.1.2 Generator 16
2.1.3 Energy Storage Apparatus 17
2.1.4 Transmission Line 19
2.2 System Related Models 19
2.2.1 Frequency 19
2.2.2 Time-Varying System Variables and Power Balance 20
2.2.3 Time Error 20
2.2.4 System Production Cost 21
2.3 Kinetic Energy Storage 22
2.4 Dynamic Power Balance 24
2.5 Generation Dispatch with Kinetic Energy Storage 27

Chapter 3. Applications and Results 29

3.1 Introduction and Data 29
3.2 KE Storage in Synchronous Generators 31
3.2.1 Generation Scheduling Formulation without Flywheels 31
3.2.2 Tests Studies 32
3.2.3 Case Comparisons and Conclusions 40
3.3 KE Storage in Synchronous Flywheels 41
3.3.1 Generation Scheduling Formulation with Synchronous Flywheels ... 41
3.3.2 Tests Studies 43
3.3.3 Case Comparisons and Conclusions 50
3.4 KE Storage in Asynchronous Flywheels 52
3.4.1 Generation Scheduling Formulation with Asynchronous Flywheels .. 54
3.4.2 Tests Studies 54
3.4.3 Case Comparisons and Conclusions 62
3.5 KE Storage and Exchange for Emergency Fast Reserve Applications 62

Chapter 4. Conclusions and Recommendations 67

4.1 Conclusions 67
4.2 Recommendations 68

• References 70

List of symbols

i :	Index identifying power system bus
j :	Index identifying time step in scheduling horizon
l :	Index identifying the generator that undergoes an outage
τ :	Time step length in hours
n :	Number of buses in power network
nt :	Number of time steps in the scheduling horizon
m :	Number of synchronous flywheels
f_{syn} :	System synchronous frequency
f^j :	System frequency at time step j
Δf_i^j :	Frequency deviation of asynchronous flywheel at bus i and time step j
Δf^j :	System frequency deviation at time step j
KE_i^j :	Kinetic energy for rotating machine at bus i and time step j
KE^{syn} :	Kinetic energy at synchronous speed
H_i :	Inertia constant for machine at bus i
S_{Bi} :	Base power for machine at bus i
S_i :	Complex power at bus i
P_{ci}^j :	Generator set point at bus i and time step j
P_{gi}^j :	Generation power at bus i and time step j
P_{KFG} :	Power derived from KE of generator
P_{KFSF} :	Power derived from KE of synchronous flywheels
P_{KFAF} :	Power derived from KE of asynchronous flywheel
P_{di0} :	Initial demand at bus i (at $j=0$)
P_{di}^j :	Power demand at bus i and time step j
P_s^j :	System power demand at time step j
P_{so} :	Initial system demand

ζ_i : Load distribution factor at bus i

P_{ik}^{j} : Power flow through line connecting bus i to bus k at time step j

R_i : Frequency regulation coefficient for the generator at bus i

k_{fi} : Load sensitivity factor at bus i

V_i^j : Line terminal voltage magnitude at bus i and time step j

δ_i^j : Voltage phase angle at bus i and time step j

X_{ik} : Reactance of the line between buses i and k

$C_i(P_{gi})$: Cost function of generation at bus i

C_{oi} : Fixed cost of generation at bus i

a_i : First order cost parameter at bus i

b_i : Second order cost parameter at bus i

λ_i : Incremental system cost (marginal price) at bus i

ΔT_e : Time error at the end of the scheduling horizon

$\Delta T_e(0)$: Initial time error at $j=0$.

ε : Maximum allowed time error at the end of the scheduling horizon

S_{SG} : Set of synchronous generators

S_{SFW} : Set of synchronous flywheels

S_{SAFW} : Set of asynchronous flywheels

List of abbreviations

KE	Kinetic Energy
ED	Economic Dispatch
OPF	Optimum Power Flow
LFC	Load Frequency Control
AGC	Automatic Generation Control
ESA	Energy Storage Apparatus
IC	Incremental Cost
SO	System Operator
SMES	Superconducting Magnetic Energy Storage
CAES	Compressed Air Energy Storage
DG	Distributed Generation

List of figures

Figure 2.1: *Daily load profile* 11

Figure 2.2: *Discretized load profile for a given time interval* 12

Figure 2.3: *Generation response and energy exchange following step changes in demand* 13

Figure 2.4: *The general model of the power system* 14

Figure 3.1: *Demand increase profile* 29

Figure 3.2: *Peak demand profile* 29

Figure 3.3: *Three-bus system with generators and loads* 31

Figure 3.4: *Power from KE of synchronous generators. Test A, Case II: With KE storage* 35

Figure 3.5: *System incremental cost (Price) variation over time. Test A, Cases I and II: Without and with KE storage in synchronous generators only* 35

Figure 3.6: *Power from KE of synchronous generators. Test B, Case II: with KE storage* 38

Figure 3.7: *System and bus incremental costs (prices) variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators only* 38

Figure 3.8: *Three bus system with generators, loads and synchronous flywheels* .. 41

Figure 3.9: *Power from KE of synchronous generators and flywheels. Test A, Case II: With KE storage* 46

Figure 3.10: *System incremental cost (Price) variation over time. Test A, Cases I and II: Without and with KE storage in synchronous generators and flywheels* 46

Figure 3.11: *Power from KE of synchronous generators and flywheels. Test B, Case II: With KE storage* 48

Figure 3.12: *System and bus incremental costs (Prices) variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators and flywheels* 48

Figure 3.13: *Three bus system with generators, loads and asynchronous flywheel* .. 52

Figure 3.14: *Power from KE of synchronous generators and asynchronous flywheel. Test A, Case II: With asynchronous flywheel* 56

Figure 3.15: *System incremental cost (Price) variation over time. Test A, Cases I and II: Without and with asynchronous flywheel. KE storage in synchronous generators and asynchronous flywheel* 56

Figure 3.16: *Power from KE of synchronous generators and asynchronous flywheel. Test B, Case II: With asynchronous flywheel* 58

Figure 3.17: *System and bus incremental costs (Prices) variation over time. Test B, Cases I and II: Without and with asynchronous flywheel. KE storage in synchronous generators and asynchronous flywheel* 59

List of tables

Table 3.1: *Basic data* 30

Table 3.2: *Bus data* 30

Table 3.3: *Line data* 30

Table 3.4: *Demand, generator power and power derived from the KE of synchronous generators. Test A, Case II* 34

Table 3.5: *System incremental costs (Prices) variation over time. Test A, Cases I and II: Without and with KE storage in synchronous generators only* 36

Table 3.6: *Demand, generator power, and power derived from the KE of synchronous generators. Test B, Case II: With KE storage* 37

Table 3.7: *System and bus incremental costs (Prices) variation over time, Test B, Cases I and II: Without and with KE storage only in synchronous generators only* 39

Table 3.8: *Power flow variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators only* 40

Table 3.9: *Demand, generator power and power derived from the KE of synchronous generators and flywheels. Test A, Case II: With KE storage* 45

Table 3.10: *Demand, generator power and power derived from the KE of synchronous generators and flywheels. Test B, Case II: With KE storage* 47

Table 3.11: *System and bus incremental costs (Prices) variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators and flywheels* 49

Table 3.12: *Power flow variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators and flywheels* 50

Table 3.13: *Demand, generator power and power derived from the KE of synchronous generators and asynchronous flywheel. Test A, Case II: With asynchronous flywheel* 55

Table 3.14: *Demand, generator power and power derived from the KE of*

	synchronous generators and asynchronous flywheel. Test B, Case II: With asynchronous flywheel	57
Table 3.15:	*System and bus incremental costs (Prices) variation over time. Test B, Cases I and II: Without and with asynchronous flywheel. KE storage in synchronous generators and asynchronous flywheel*	60
Table 3.16:	*Power flow variation over time. Test B, Cases I and II: Without and with asynchronous flywheel. KE storage in synchronous generators and asynchronous flywheel*	61

Chapter-I Introduction and Background

1.1 Introduction

Within large power systems, kinetic energy is stored in the rotating masses of the electric machines. Under both normal and emergency operating conditions, this energy is utilized to compensate for power imbalances and to damp out generator and motor load angle swings. In electricity markets, a price spike, depending on its size and extent, can constitute an emergency, and as such, one could argue that the use of stored kinetic energy to respond to such an event is equally justified. Assuming that KE in sufficient amounts can be stored and released, its judicious use could reduce the total cost, stabilize electricity prices, and relieve transmission line congestion without endangering power system operation. In addition, stored KE could be used as fast reserve in primary frequency regulation following the loss of a generating unit or a sudden increase in demand.

Modern Energy Management Systems are equipped with automatic generation control (AGC) systems that allow changes in the system reference frequency. The normal use of this feature is to correct accumulated frequency deviations, which manifest themselves as a time error in electric clocks.

To ensure that there is enough KE storage capacity within a power system to meet the abovementioned objectives, additional support in the form of energy storage apparatus (ESA) is considered in this thesis. Two types of ESA are proposed. The first type is synchronous flywheels which operate within the allowable range of the synchronous frequency. The second type is asynchronous flywheels whose rotational speed is independent from the system synchronous frequency and can vary over a wide range. This feature gives the asynchronous flywheel the ability to store and release significant amounts of KE. To test the technical feasibility of the proposed concepts, it is assumed in this thesis that one can install as many flywheels as required, disregarding at this stage the capital and installation costs of such devices.

KE exchanges can take place in both generating and motoring modes. When the electricity prices are low, energy is taken from the prime sources (water, coal, nuclear energy) and stored in the form of KE in the rotating machines by increasing their speed of rotation. This stored energy is taken away from the rotating masses by lowering their speed when the energy prices are high. This process takes place without affecting the security of the system, but taking into account the economic performance of the power systems.

When the physical power system runs into a condition that requires the use of the stored KE, due to the slow response of the normal power system controls, initially the laws of physics governing the power system determine the amount of stored kinetic energy that should be deployed. In the financial world, on the other hand, the laws governing such activities are the market rules and there is often enough time to carefully determine the appropriate amount of KE that has to be converted into marketable energy and ensure that the use of this energy is consistent with the power system reliable operation.

1.2 Scope of Thesis

The goal of this research is to take advantage of the allowed speed deviation of rotating machines by using it as a tool for KE storage and exchange to help reduce total operational costs, to moderate the energy market prices and to help in transmission line congestion management. This needs to be done while respecting equipment limitations such as line flow limits.

This objective will be tested with existing synchronous generators and motors, as well as by adding synchronous and asynchronous flywheels to the system.

This thesis also examines how to use stored KE as fast reserve in primary frequency regulation following the loss of a generating unit or a sudden increase in demand.

1.3 Background

1.3.1 Power Flow

A typical power system consists of a large number of generators and loads interconnected by hundreds of high-voltage transmission lines. The network buses represent power plants, switch yards, load centers and voltage-support sub-stations. At each bus, the power flow equations govern the balance between the generated power, the power demand and the power leaving the bus into the network. The important features of power system security analysis can be summarized as follows: [1,2]

- The net power injected into the system should be equal to the net power consumed by the system plus the losses;
- There are stability and thermal limits on transmission lines that should not be violated;
- It is necessary to keep the voltage levels within operationally acceptable limits;
- In the case of interconnected power systems, contractual power transfers between control areas should be enforced;
- A proper pre-fault power flow strategy has to be taken into account to avoid system collapse after any of a set of credible outages.

The net complex power, S_i, injected into bus i is denoted by: [20]

$$S_i = \left(P_{gi} - P_{di}\right) + j\left(Q_{gi} - Q_{di}\right) \tag{1.1}$$

where P_{gi} and Q_{gi} are the generated real and reactive generation powers, while P_{di} and Q_{di} are the real and reactive demands. Equation (1.1) can be also expressed in terms of the complex bus voltages at all other network buses and of the complex network admittance matrix:

$$S_i = P_i + jQ_i = V_i \sum_{k=1}^{n} I_{ik}^* = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^* \tag{1.2}$$

where V_i is the complex voltage at bus i, V_k^* is the complex conjugate of the voltage at bus k and Y_{ik} is the $(i,k)^{th}$ element of the bus admittance matrix. Writing the real and imaginary parts of (1.2) in polar coordinates gives the load flow equations:

$$P_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \cos(\delta_i - \delta_k + \theta_{ik}) \tag{1.3}$$

$$Q_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \sin(\delta_i - \delta_k + \theta_{ik}) \tag{1.4}$$

where δ_i is the voltage phase angle at bus i and θ_{ik} is the angle of the $(i,k)^{th}$ element of the bus admittance matrix.

1.3.2 Load Frequency Control (LFC)

The basic role of LFC is to maintain the balance between system generation and demand and to keep the frequency and tie line flows at their scheduled values [1].

LFC is a controller for the speed governor system in the generator primary control loop. The governor of unit i has two inputs, ΔP_{ci} , the incremental set point defined by the LFC, and Δf, the system frequency deviation. Under steady state conditions, the incremental generation of unit i is given by,

$$\Delta P_{gi} = \Delta P_{ci} - \frac{1}{R_i} \Delta f \tag{1.5}$$

where R_i is the generator regulation or droop in Hz/MW. Thus, a change in the power generation, ΔP_{gi} , is a result of either from a change in the set point, ΔP_{ci} , or in the system frequency, Δf.

Combining (1.5) with the load flow equations, if there is a change in the load or the generation, a new power flow balance is established, causing a shift in frequency and a change in the stored kinetic energy [1]. The latter can be expressed in terms of the new system frequency, f, and the KE at the normal frequency, f_{syn},

$$KE_i = KE_i^{syn}\left(\frac{f}{f_{syn}}\right)^2 \quad ; \qquad (1.6)$$

1.3.3 Economic Dispatch

Economic Dispatch (ED), also called optimum generation dispatch, is a feasible dispatch that minimizes the total fuel cost, C, defined by,

$$\sum_{i=1}^{n} C_i(P_{g_i}) \quad ; \qquad (1.7)$$

Typically, $C_i(P_{g_i})$ can be represented as:

$$C_i(P_{g_i}) = C_{0i} + a_i P_{g_i} + \frac{b_i}{2} P_{g_i}^2 \qquad (1.8)$$

where,

C_{0i} : The fixed cost [\$/h]

$a_i P_{g_i} + \frac{b_i}{2} P_{g_i}^2$: The variable cost [\$/h]

The goal of the system operator is to dispatch the n scheduled generators so as to minimize their overall production cost. Usually ED runs every five minutes in the energy control center which has links to various power plants via communication channels.

The solution of such problem can be found by the method of Lagrange. If we assume that the P_{gi} limits are not reached, the Lagrangian function can be expressed as:

$$L(P_{g_i},\lambda)=\sum_{i=1}^{n}C_i(P_{g_i})-\lambda(\sum_{i=1}^{n}P_{g_i}-P_d) \; ; \tag{1.9}$$

The necessary conditions for P_{gi} to be an optimal solution are:

1- Equal incremental costs : $IC_i(P_{gi})=\dfrac{dC_i(P_{g_i})}{dP_{g_i}}-\lambda=0$;

2- The power balance : $\sum_{i=1}^{n}P_{g_i}=P_d$.

These two conditions can be easily solved for the optimum generation dispatch and for the system incremental cost, λ.

1.3.4 Optimal Power Flow

Ideally, a power system should be operated to dispatch generation as economically as possible but without transmission limit violations. To ensure that these conditions are met, the ED is combined with the power flow (PF) equations to formulate what is known as the optimum power flow (OPF) [3].

Simply stated, OPF is a more general type of ED that also accounts for network constraints. These constraints could be the line flow limits only, but could also include voltage and reactive generation limits.

If we ignore reactive power limits, the OPF takes the form: [21]

Minimize :

$$C=\min\sum_{i=1}^{n}C_i(P_{g_i}) \tag{1.10}$$

subject to,

$$\sum_{i=1}^{n} P_{g_i} - P_{di} = P_i(\delta, V) \tag{1.11}$$

$$r_i(P_{gi}, V_i, \delta_i) \le 0 \tag{1.12}$$

$$h_k(\delta, V) \le 0 \tag{1.13}$$

where,

P_{gi}, P_{di} are the real power generation and demand at bus i respectively,

$P_i(\delta, V)$ is the real power injection into the network at bus i,

$r_i(P_{gi}, V_i) \le 0$ is a set of local constraints, such as generation and voltage limits,

$h_k(\delta, V) \le 0$ represents the maximum power transfer limit in transmission line k.

The equality constraints in (1.11) correspond to the set of load flow equations. The inequality constraints in (1.12) are usually expressed in the form:

$$P_{g_i}^{\min} \le P_{g_i} \le P_{g_i}^{\max} \tag{1.14}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{1.15}$$

while (1.13) corresponds to the limits on the transmission line flows:

$$-P_{fk}^{\max} \le P_{fk}(\delta, V) \le P_{fk}^{\max} \; ; \tag{1.16}$$

In addition, to ensure stability, constraints may be imposed on the line angle differences:

$$|\delta_i - \delta_k| \le \delta^{\max} \; ; \tag{1.17}$$

1.3.5 Energy Storage Technologies

Several technologies have been developed for energy storage applications, each with its own special features. Energy storage technologies can be divided into two groups: [12]

- DC-based devices including superconducting magnetic energy storage (SMES), batteries and capacitors;
- Inertia-based devices like flywheels, hydro-pumps, and compressed air energy storage (CAES).

SMES :

In superconducting magnetic energy storage, energy is stored in the form of a magnetic field by passing a dc current through a set of superconducting coils. The benefit of this type of energy storage is the absence of resistive losses and the fast response in energy transfer (charging or discharging).

Batteries :

In batteries, the energy is stored in electrochemical form by creating electrically charged ions, and released in the opposite way. The flow of electrons takes place at a rate limited by the chemical reaction rates.

Capacitors :

Here, energy is stored in the electric field between two charged plates separated by an insulating material called the dielectric. The energy is stored in the device according to the voltage applied across the plates. Capacitors are only good for small amounts of energy storage.

Flywheels :

The flywheel is a kinetic energy (KE) storage device in which the KE is stored in its rotating mass. The electrical energy is transmitted into and out of the flywheel system by a variable frequency field motor/generator. The control of energy exchange happens through an AC/AC converter. The advantage of a flywheel is the direct conversion of kinetic energy to electrical energy with a very high efficiency plus the significant amount of energy that can be stored in the device.

Hydro-Pump :

Here, energy storage takes place by storing water in reservoirs. Electrical energy is produced by releasing the water at high speed through turbines into lower reservoirs. Then, water is pumped up to the upper reservoir in order to store it again and the cycle is repeated.

CAES :

Compressed air energy storage systems store energy by compressing air within an air reservoir during the charging period. At the time of discharging, the machine works as a generator by transferring the mechanical power (from the air pressure) into electrical power. A special clutch is used for the machine to operate in both regimes (motor/generator).

1.4 Thesis Outline

1.4.1 Chapter 2

Chapter 2 presents the analytical part of the thesis, introducing the device and system models used. First, the concept of KE storage is considered in conjunction with the frequency deviation in a typical power system. Then, basic models for synchronous and asynchronous flywheels are developed.

The models describe device behavior under steady-state and dynamic conditions. The dynamic models are needed to represent the storage and release of energy, which are related to frequency/speed changes. The steady-state models are used to formulate system operation in the presence of storage devices as a scheduling problem.

1.4.2 Chapter 3

In chapter 3, numerical simulations are carried out to simulate the optimum process of storing and releasing KE for three different load profiles. The benefits of storing and releasing KE on cost, prices, as well as in congestion management are analyzed.

1.4.3 Chapter 4

Chapter 4 contains the conclusions as well as some recommendations for future work.

Chapter 2: Theoretical Development

The study reported in this thesis is based on a typical 24-hour system load profile as illustrated in Fig. 2.1. Within this profile, two types of time interval are chosen for further analysis, each characterizing a different system demand variation:

- Steady demand increase;
- Around the peak demand.

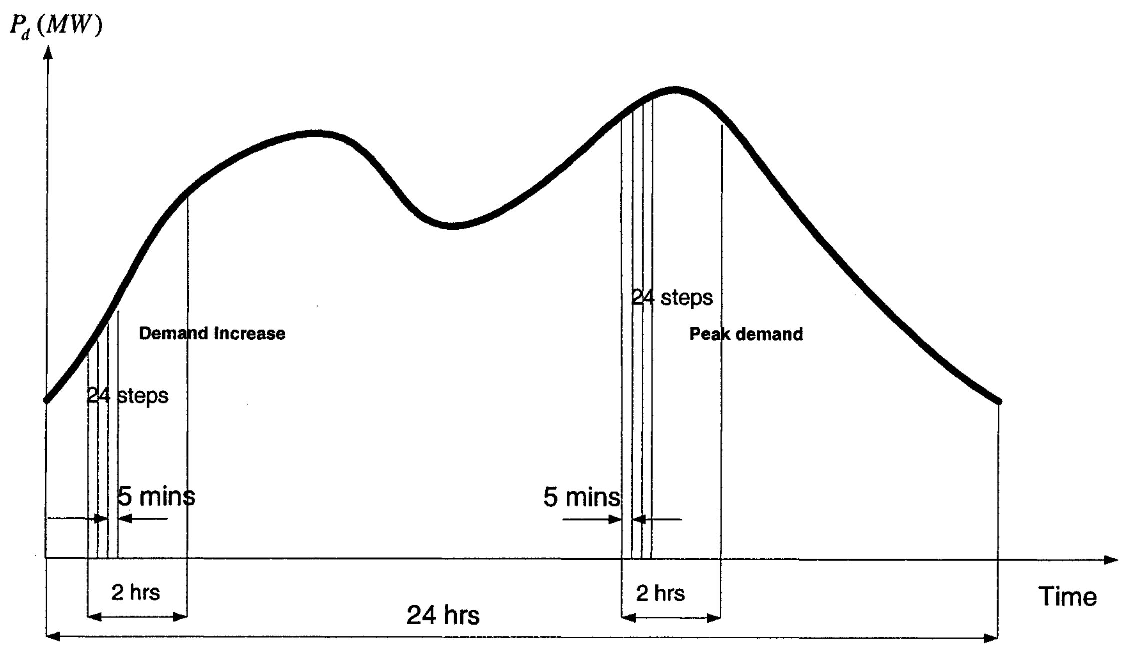

Figure-2.1: *Daily load profile.*

Both types of time intervals are divided into *nt* time steps, each with a duration of τ minutes, indexed by the variable j ranging from $j=1$ to $j=nt$. The load is then discretized as shown in Fig. 2.2.

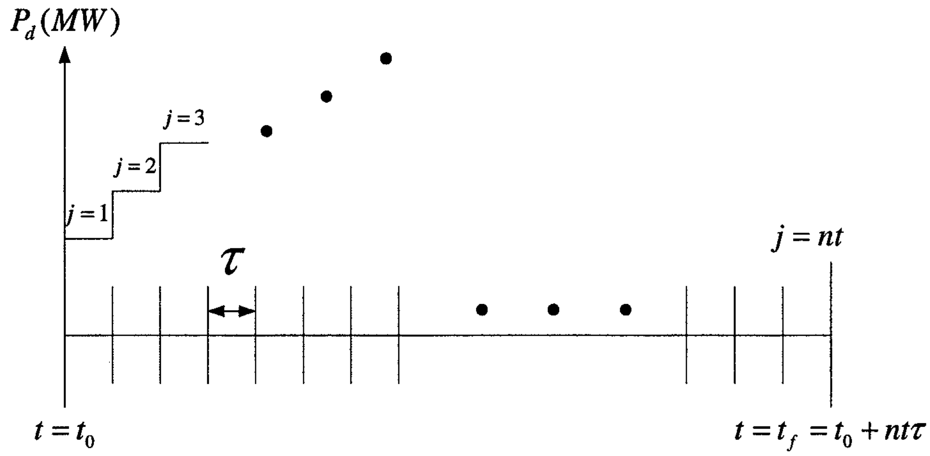

Figure-2.2: *Discretized load profile for a given time interval.*

The two types of load profile behavior are analyzed in this thesis to show how the process of storing and releasing kinetic energy (KE) can be coordinated to reduce cost and nodal marginal prices as well as relieving transmission congestion. Two examples of how KE can be so coordinated are shown in Fig. 2.3 which depicts the response of the total generation and system frequency following a sequence of step changes in the demand. In the example on the left of the figure where the load profile goes through a peak, KE is stored during the first two time steps and released in the third time step. In the example on the right of the figure, the load increases continuously. Here, during the first two steps KE is stored to be released during the last steps. This thesis will show how this coordination of KE can be formulated and solved using mathematical programming techniques.

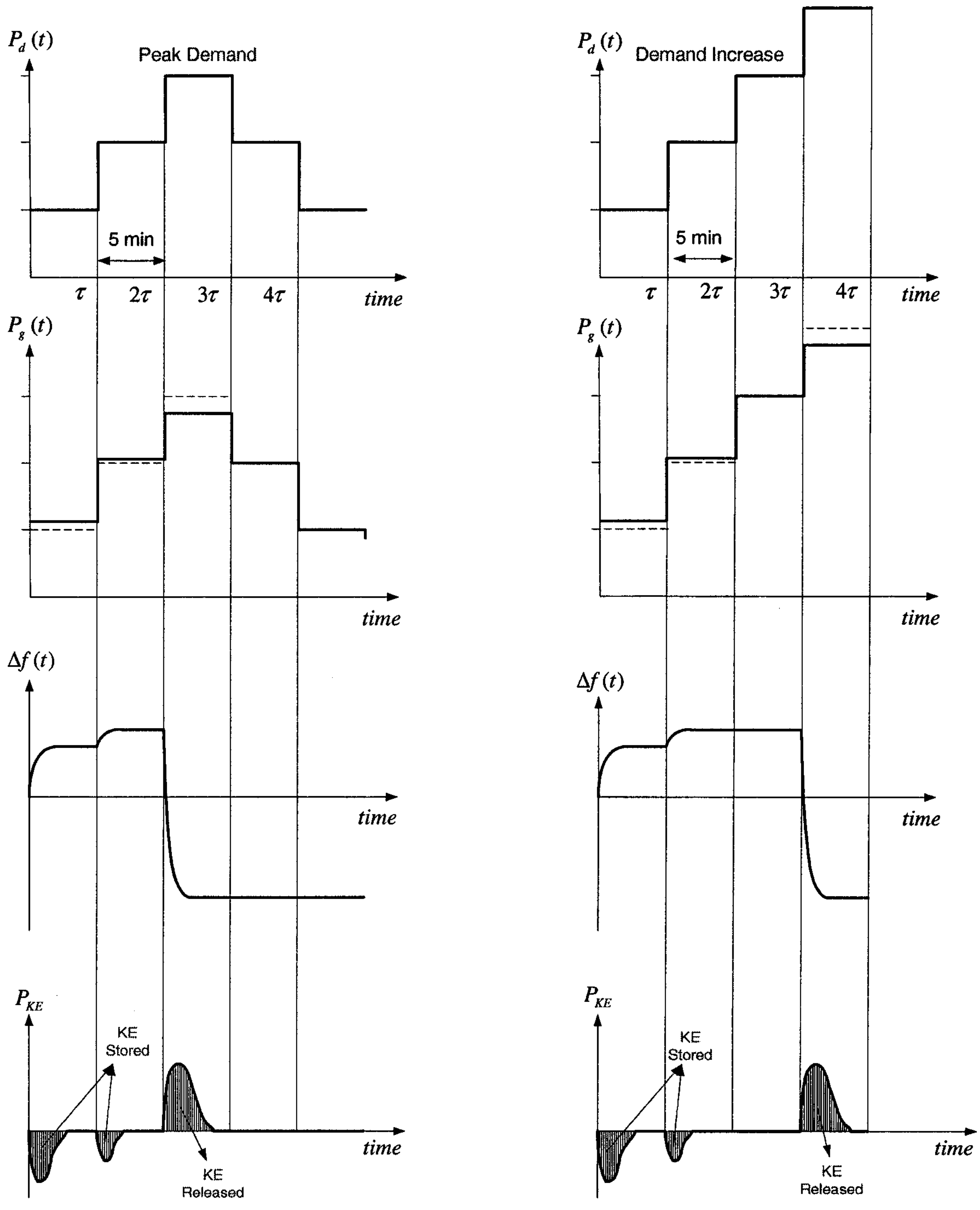

Figure 2.3: *Generation response and energy exchange following step changes in demand*

The power system model considered in this thesis is as shown in Fig. 2.4. It consists of synchronous generators, loads, energy storage apparatus and the power transmission network.

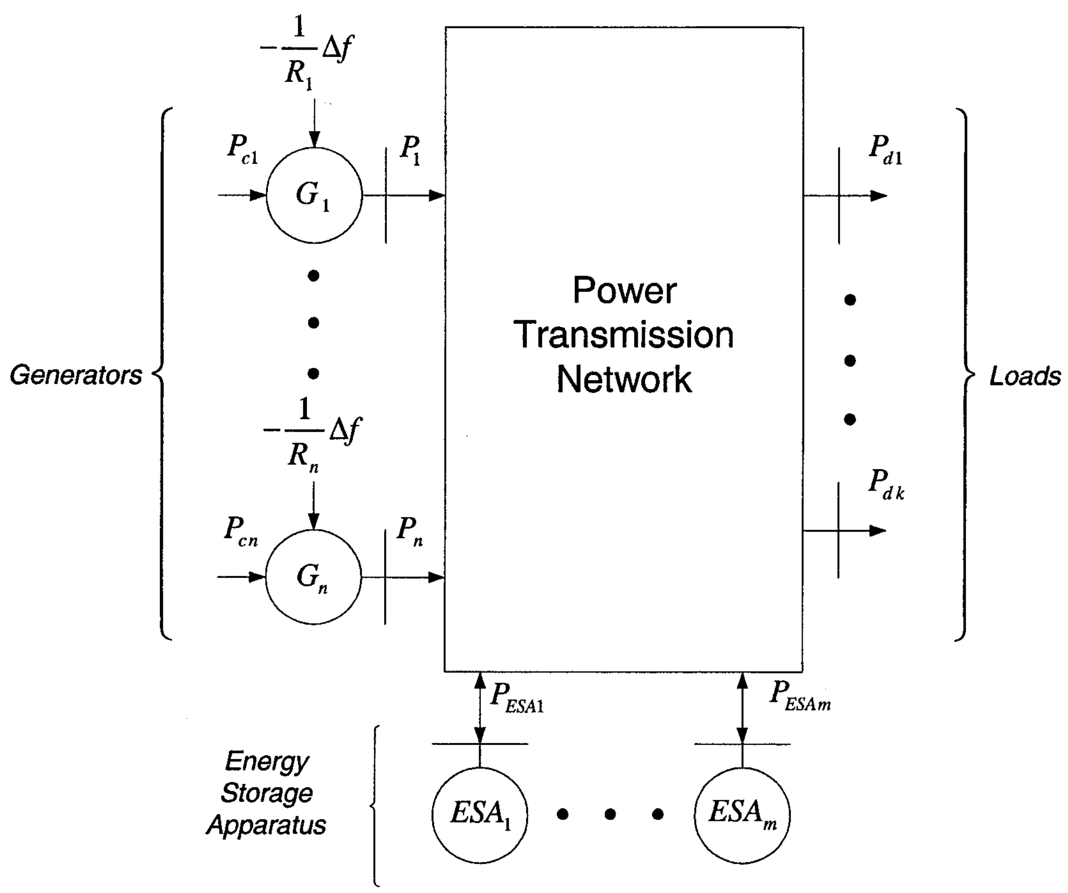

Figure 2.4: *The general model of the power system.*

This chapter now introduces a number of specific models that will be used throughout the thesis. First, we will describe device models for:

- Loads
- Generators
- Energy Storage Apparatus
- Transmission lines

In addition, system models will be described for:

- System Frequency
- Time-Varying System Variables
- Time Error
- Generation Cost
- Kinetic Energy Storage

2.1 Device Models

2.1.1 Load

Bus loads are nonlinear functions of the system frequency, f. Around the synchronous frequency, f_{syn}, loads can be approximated by a linear function of $\Delta f = f - f_{syn}$ of the form:

$$P_{di} = \varsigma_i P_{s0}(1 + k_{fi}\Delta f)\,; \qquad (\forall i = 1,\cdots n) \tag{2.1}$$

Where P_{s0} represents the value of system demand at $\Delta f = 0$. In general P_{s0}, ς_i, k_{fi} can change with time, however, in this thesis both ς_i, k_{fi} are assumed to remain fixed.

Loads are modeled at the level of transmission network buses, by relating them to the system demand through relations of the form:

$$P_{di} = \varsigma_i P_s\,; \tag{2.2}$$

We also define,

$$P_{di0} = \varsigma_i P_{s0} \tag{2.3}$$

where ς_i represents the load distribution factor for bus i, defined to satisfy:

$$\sum_{i=1}^{n} \varsigma_i = 1; \qquad (\varsigma_i \geq 0) \tag{2.4}$$

2.1.2 Generator

The generator model has two forms: The dynamic model which describes the generation behavior in the first few seconds during transients, and the steady-state model. Dynamic models are used in this thesis to capture the behavior of generation, frequency, and the production cost function following a step change in demand. The steady-state model is formulated by the power flow problem when all transients have died down.

a. Generator Dynamic Model

The dynamic model of an arbitrary generator *i* is restricted here to its rotor subsystem swing equation which is given by:

$$\frac{df_i}{dt} = \frac{f_{syn}}{2H_i}\left[P_{gi} - P_{di} - P_i(\underline{\delta})\right]; \quad \forall i \in S_{SG} \tag{2.5}$$

where S_{SG} is the set of synchronous generators.

The governor subsystem relation is,

$$P_{gi} = P_{ci} - \frac{1}{R_i}\Delta f_i \tag{2.6}$$

where $\Delta f_i = f_i - f_{syn}$ is the speed variation of machine *i* relative to the synchronous speed, and R_i is the regulation parameter characterizing the ability of the machine to stabilize its speed.

b. Steady-state Model

Under steady-state conditions:

$$\frac{df_i}{dt} = 0 \quad ; \tag{2.7}$$

If the power system is asymptotically stable, the rotational speeds of all generators approach the system frequency; i.e. $\Delta f_i \to \Delta f$. Therefore at bus *i*:

$$P_{ci} - \frac{1}{R_i}\Delta f - P_{di0} - P_{di0}k_{fi}\Delta f = P_i(\underline{\delta}) \; ;$$

Then,

$$\Delta f = \frac{1}{\beta_i}[P_{ci} - P_{di0} - P_i(\underline{\delta})] \tag{2.8}$$

where,

$$\beta_i = \frac{1}{R_i} + P_{di0}k_{fi} \quad ; \tag{2.9}$$

The generation outputs must also satisfy some technical limits:

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \quad ; \tag{2.10}$$

2.1.3 Energy Storage Apparatus

The role of Energy Storage Apparatus (ESA) can be played by the existing rotating masses of the synchronous generators and motors, as well as by two types of flywheels, namely synchronous and asynchronous. The latter could be installed throughout the system to be able to store a more significant amount of KE than that available in the existing synchronous machines of a typical power system.

- Synchronous Flywheels

These are synchronized with the system frequency and behave as either motors or generators. In contrast to generators that are connected to a power plant supplying them with power, flywheels have no source of energy other than what they can absorb through the transmission network from the existing generators. When acting as a motor, a flywheel absorbs KE which is stored in its rotating mass as an increase in frequency. When acting as a generator, a flywheel releases KE to the network by decreasing its frequency of rotation.

Thus under steady-state conditions, the power output of the flywheel can be presented as:

$$P_{gi} = -\frac{1}{R_i}\Delta f; \quad \forall i \in S_{SF} \tag{2.11}$$

where S_{SF} is the set of synchronous flywheels. The power limits of a flywheel are directly dependent on the system frequency deviation limits, that is,

$$-\frac{1}{R_i}\Delta f^{\min} \leq P_{gi} \leq -\frac{1}{R_i}\Delta f^{\max}; \quad \forall i \in S_{SF} \tag{2.12}$$

The allowable frequency deviation for synchronous machines and flywheels is typically within *500 mHz* of the synchronous frequency.

- Asynchronous Flywheel

These are not synchronized with the system frequency as with synchronous flywheels, and can operate over a much broader range of speed. Since their power output is limited by the same relation as the synchronous flywheels (2.12), the range of power output of asynchronous flywheels is also much broader.

2.1.4 Transmission Lines

In this thesis, some reasonable simplifying assumptions are made with regard to the transmission network:

- Bus voltage magnitudes are maintained at *1 p.u.*;
- Line ohmic losses are ignored;
- Line voltage phase angle differences are assumed small enough so that $\sin(\delta_i - \delta_k) \approx (\delta_i - \delta_k)$.

With these assumptions, the real line flow between buses *i* and *k* can be represented by:

$$P_{ik} = \frac{V_i V_k \sin(\delta_i - \delta_k)}{X_{ik}} \approx \frac{(\delta_i - \delta_k)}{X_{ik}} \quad ; \qquad (2.13)$$

In addition, line power flows are generally restricted by thermal or stability limits:

$$-P_{ik}^{\max} \leq P_{ik} \leq P_{ik}^{\max} \quad ; \qquad (2.14)$$

Transformers are modeled by their equivalent π-circuits ignoring magnetizing currents.

2.2 System Related Models

2.2.1 Frequency

The system frequency, f, is the value at which all the synchronous rotating machines operate in steady-state. To ensure that this frequency does not attain unreasonable values, limits are imposed of the form:

$$|\Delta f| \leq \Delta f^{\max} \quad ; \qquad (2.15)$$

Typically the maximum allowed frequency range is ±500 *mHz*.

2.2.2 Time-Varying System Variables and Power Balance

Here, we introduce the notion of time-varying system variables, indexed by the time step *j*. We assume reasonably that the length of each time step, τ, (in this thesis, taken to be *5* minutes) is long enough for all transients to have settled to the steady-state levels following a jump in the discretized levels of demand, P_{di}^{j}. The steady-state system frequency deviation at the end of step *j* is denoted by Δf^{j}. This frequency deviation is defined by the kinetic energy at the end of time step *j*, KE_i^j, which is related to the kinetic energy stored at the end of the previous time step *j-1*, KE_i^{j-1}, plus the kinetic energy gained during time step *j*. This gain in kinetic energy can be expressed as,

$$KE_i^j - KE_i^{j-1} = \int_{(j-1)\tau}^{j\tau} \left(P_{gi}(t) - P_{di}(t) - P_i(\underline{\delta}(t)) \right) dt \ ; \qquad (2.16)$$

Since the behaviour of the power balance inside the integral is a transient pulse (see Fig. 2.3), we define the average generated and injected powers over time step *j*, respectively, P_{gi}^j and $P_i(\delta^j)$, by the relation,

$$KE_i^j - KE_i^{j-1} = \left(P_{gi}^j - P_{di}^j - P_i(\underline{\delta}^j) \right)\tau \qquad (2.17)$$

which is an approximation of (2.16).

2.2.3 Time Error

When Δf^{j}, differs from zero, in other words when the system frequency f^{j} differs from f_{syn}, the time as measured by the system frequency will be in error. For a time horizon of *nt* time steps, each of duration τ, the incremental time error, ΔT_e, can then be computed as,

$$\Delta T_e = \frac{\sum_{j=1}^{nt} \Delta f^j \tau}{f_{syn}} \quad ; \qquad (2.18)$$

The total time error can be found by adding the incremental term ΔT_e to the accumulated time error existing at the beginning of the scheduling period, $\Delta T_e(0)$.

Typically, it may be required that at the end of the scheduling horizon the time error be smaller than a specified value, ε, that is,

$$\left| \Delta T_e(0) + \frac{\tau}{f_{syn}} \sum_j \Delta f^j \right| \leq \varepsilon \quad ; \qquad (2.19)$$

2.2.4 System Production Cost

The objective of the system operator is generally to minimize the total production cost over the scheduling horizon:

$$C = \sum_j \sum_i C_i \left(P_{gi}^j \right) \tau \quad ; \qquad (2.20)$$

Assuming quadratic generation cost functions, $C_i\left(P_{gi}^j\right) = a_i P_{gi}^j + \frac{b_i}{2}\left(P_{gi}^j\right)^2$, the system production cost can be expressed by,

$$C = \min \sum_j \sum_i \left(a_i P_{gi}^j + \frac{b_i}{2} \left(P_{gi}^j \right)^2 \right) \tau \quad ; \qquad (2.21)$$

In the above model, the cost of energy during the transient period following a step change in demand is neglected as it is very small compared to the cost during the steady state period.

2.3 *Kinetic Energy Storage*

Three forms of KE storage systems are studied in this thesis: Synchronous generators, synchronous flywheels, and asynchronous flywheels.

In general, the KE of an arbitrary synchronously rotating machine i at time step j, is given by,

$$KE_i^j = \frac{1}{2} J_i (f^j)^2 \tag{2.22}$$

where J_i is the moment of inertia of the machine and here f^j is in rad/s. Asynchronous flywheels do not have to turn at a common synchronous speed, so that each one has its own speed of rotation, f_i^j. Thus its KE at time j is,

$$KE_i^j = \frac{1}{2} J_i (f_i^j)^2 \ ; \tag{2.23}$$

When turning at synchronous speed, the KE of any machine i is given by,

$$KE_i^{syn} = \frac{1}{2} J_i f_{syn}^2 \ ; \tag{2.24}$$

The inertia constant of any machine i is defined by,

$$H_i \triangleq \frac{KE_i^{syn}}{S_{Bi}} \tag{2.25}$$

where S_{Bi} is the machine's base power rating. Thus, the kinetic energy of a synchronous machine can be expressed by,

$$KE_i^j = \frac{1}{2} J_i f_{syn}^2 \frac{\left(f^j\right)^2}{f_{syn}^2} = H_i S_{Bi} \frac{\left(f^j\right)^2}{f_{syn}^2} \tag{2.26}$$

while for an asynchronous flywheel, the KE in terms of the *H* constant is,

$$KE_i^j = \frac{1}{2} J_i f_{syn}^2 \frac{\left(f_i^j\right)^2}{f_{syn}^2} = H_i S_{Bi} \frac{\left(f_i^j\right)^2}{f_{syn}^2} \quad ; \tag{2.27}$$

The amount of KE stored at time step *j* can also be expressed in terms of the corresponding frequency deviation. Thus, for a synchronous machine,

$$\begin{aligned} KE_i^j &= H_i S_{Bi} \frac{\left(f^j\right)^2}{f_{syn}^2} = H_i S_{Bi} \frac{\left(f_{syn} + \Delta f^j\right)^2}{f_{syn}^2} \\ &= KE_i^{syn} \left(1 + \frac{\Delta f^j}{f_{syn}}\right)^2 \simeq KE_i^{syn} \left(1 + 2\frac{\Delta f^j}{f_{syn}}\right) \end{aligned} \tag{2.28}$$

while for an asynchronous flywheel we have,

$$\begin{aligned} KE_i^j &= H_i S_{Bi} \frac{\left(f_i^j\right)^2}{f_{syn}^2} = H_i S_{Bi} \frac{\left(f_{syn} + \Delta f_i^j\right)^2}{f_{syn}^2} \\ &= KE_i^{syn} \left(1 + \frac{\Delta f_i^j}{f_{syn}}\right)^2 \end{aligned} \quad ; \tag{2.29}$$

As an example, for synchronous machines in standard power systems, assuming that the maximum frequency deviation is ±600 mHz or ± 1% of 60 Hz, then, from (2.26) the maximum amount of KE exchange is approximately 2% of the KE stored in the rotating masses at synchronous speed. For example, in a power system with 200 identical synchronous machines each rated at 50 MVA with an *H* constant of 5s, the KE stored at synchronous speed in each generator is $HS_B = 5 \times 50 = 250$ MJ. Thus, the KE that can be exchanged within a frequency deviation range of ±600 mHz is approximately 2% of this amount or 5MJ per synchronous machine. Since there are 200 units in this system, the total maximum KE that can be exchanged is 1000 MJ.

This means that if the system operator allows the system frequency to increase to 60.6 Hz, then he has stored 1000 MJ of additional kinetic energy, which can be released under his control for either emergency or economic reasons. For example, the 1000 MJ could be released at the rate of 100 MW over 10*s* for emergency purposes such as congestion relief or to provide fast reserve after a sudden increase in demand or loss of generator.

For asynchronous flywheels, the amount of energy that can be exchanged could be up to 50 times greater than for synchronous units if 100% of the KE stored is used by the operator (assuming that such devices can operate from zero to maximum speed).

2.4 Dynamic Power Balance

The synchronous KE energy storage devices are the synchronously rotating machines in the power system (both generators and motors). The level of KE stored at time j in the rotating generator i is controlled by their centrally adjusted set points, P_{ci}^j, through the relation,

$$P_{gi}^j = P_{ci}^j - \frac{\Delta f^j}{R_i}; \quad \forall i \in S_{SG} \tag{2.30}$$

During KE storage periods, the generator set points are raised to levels above what is needed to satisfy the system demand. As a result, the system frequency rises. During KE release periods, the generator set points are lowered to levels below what is needed to satisfy the system demand. As a result, the system frequency drops.

Although the set points of synchronous motors cannot be centrally controlled, these devices still store and release KE through their system frequency dependence,

$$P_{di} = \varsigma_i P_{s0}(1 + k_{fi}\Delta f);$$

The dynamic power balance for synchronous generators, that is, $\forall i \in S_{SG}; \forall j$, is then,

$$\begin{aligned} KE_i^j - KE_i^{j-1} &= \left(P_{gi}^j - P_{di}^j - P_i(\underline{\delta}^j)\right)\tau \\ &= \left(P_{ci}^j - \frac{\Delta f^j}{R_i} - P_{di}^j - P_i(\underline{\delta}^j)\right)\tau \end{aligned} \qquad (2.31)$$

where,

$$KE_i^j = KE_i^{syn}\left(1 + \frac{\Delta f^j}{f_{syn}}\right)^2$$

and where each the frequency deviation must respect,

$$\Delta f^{\min} \le \Delta f^j \le \Delta f^{\max}; \qquad \forall i \in S_{SG} \qquad (2.32)$$

Synchronous flywheels behave like synchronous generators with frequency regulation but without set points, that is,

$$P_{gi}^j = -\frac{1}{R_i}\Delta f^j; \qquad \forall i \in S_{SF} \qquad (2.33)$$

Thus, as defined by (2.33), since there is no controllable set point, the power generated or consumed by a synchronous flywheel, P_{gi}^j, must follow the system frequency and cannot be controlled other than by centrally controlling the system frequency.

The dynamic power balance for synchronous flywheels, that is, $\forall i \in S_{SF}; \forall j$, is then,

$$\begin{aligned} KE_i^j - KE_i^{j-1} &= \left(P_{gi}^j - P_{di}^j - P_i(\underline{\delta}^j)\right)\tau \\ &= \left(-\frac{\Delta f^j}{R_i} - P_{di}^j - P_i(\underline{\delta}^j)\right)\tau \end{aligned} \tag{2.34}$$

where,

$$KE_i^j = KE_i^{syn}\left(1 + \frac{\Delta f^j}{f_{syn}}\right)^2;$$

In addition, each synchronous flywheel has limits on the frequency deviation, that is,

$$\Delta f^{\min} \leq \Delta f^j \leq \Delta f^{\max}; \quad \forall i \in S_{SF} \tag{2.35}$$

Asynchronous flywheels behave like synchronous generators in that they also have frequency regulation without set points. However, each asynchronous flywheel, unlike synchronous machines, has its own rotating speed, which can be controlled centrally by the system operator (SO). Since the speed can be controlled, the speed regulation droop-term, $-\frac{\Delta f}{R}$, is not present. Hence, for asynchronous flywheels, $P_{gi}^j = 0$.

The only power that can be injected into or extracted from an asynchronous flywheel is due to a change in speed (or KE). The dynamic power balance for asynchronous flywheels, that is, $\forall i \in S_{AF}; \forall j$, is then,

$$\begin{aligned} KE_i^j - KE_i^{j-1} &= \left(P_{gi}^j - P_{di}^j - P_i(\underline{\delta}^j)\right)\tau \\ &= \left(-P_{di}^j - P_i(\underline{\delta}^j)\right)\tau \end{aligned} \tag{2.36}$$

where,

$$KE_i^j = KE_i^{syn}\left(1 + \frac{\Delta f_i^j}{f_{syn}}\right)^2;$$

In addition, each asynchronous flywheel has limits on the frequency deviation, that is,

$$\Delta f_i^{\min} \le \Delta f_i^{\,j} \le \Delta f_i^{\max}; \quad \forall i \in S_{AF} \tag{2.37}$$

Because of these limits, if the KE of a rotating machine reaches its upper (lower) limit, then it cannot absorb (release) any more energy.

2.5 Generation Dispatch with Kinetic Energy Storage

Generation dispatch with KE storage tries to take advantage of the potential to store or release energy in order to find a better feasible dispatch. The objective function can be to minimize the total production cost over all generators over the entire time horizon taking into account the KE storage capabilities of all rotating machines. From the previous sections, mathematically this takes the form,

Objective Function: $$\boxed{C = \sum_{j=1}^{nt} \sum_{i \in S_{SG}} C_i(P_{gi}^j)\tau} \;;$$

subject to,

Generator Model: $$P_{gi}^j = P_{ci}^j - \frac{1}{R_i}\Delta f^{\,j} \;; \qquad \forall i \in S_{SG},\ \forall j$$

Load Model: $$P_{di}^j = \varsigma_i P_{s0}^j \left[1 + k_{fi}\Delta f^{\,j}\right] \;; \quad \forall i, j$$

Energy Balance:
$$\begin{cases} KE_i^j = KE_i^{j-1} + \tau\left[P_{ci}^j - \dfrac{\Delta f^j}{R_i} - P_{di}^j - P_i(\underline{\delta}^j)\right]; \ \forall i \in S_{SG} \\ KE_i^j = KE_i^{j-1} + \tau\left[-\dfrac{\Delta f^j}{R_i} - P_{di}^j - P_i(\underline{\delta}^j)\right]; \ \forall i \in S_{SF} \\ KE_i^j = KE_i^{j-1} + \tau\left[-P_{di}^j - P_i(\underline{\delta}^j)\right]; \ \forall i \in S_{AF} \end{cases}$$

Kinetic Energy:
$$\begin{cases} \begin{cases} KE_i^j = KE_i^{syn}\left[1 + \dfrac{\Delta f^j}{f_{syn}}\right]^2 & ; \quad \forall i \in S_{SG}, S_{SF}, \forall j \\ KE_i^{syn} = H_i S_{Bi} \end{cases} \\ \begin{cases} KE_i^j = KE_i^{syn}\left[1 + \dfrac{\Delta f_i^j}{f_{syn}}\right]^2 & ; \quad \forall i \in S_{AF}, \forall j \\ KE_i^{syn} = H_i S_{Bi} \end{cases} \end{cases} ;$$

Time Error:
$$\Delta T_e = \sum_j \left(\frac{\Delta f^j}{f_{syn}}\right)\tau \ ;$$

Inequality Constraints:
$$\begin{cases} P_{gi}^{\min} \le P_{gi}^j \le P_{gi}^{max}; & \forall i \in S_{SG} \\ \left|P_{ik}(\underline{\delta}^j)\right| \le P_{ik}^{max}; & \forall j \\ \left|\Delta T_e\right| \le \ \Delta T_e^{max} \ ; \end{cases}$$

Frequency limits :
$$\begin{cases} \Delta f^{\min} \le \Delta f^j \le \Delta f^{\max} \ ; \ \forall i \in S_{SG}, S_{SF}, \ \forall j \\ \Delta f_i^{\min} \le \Delta f_i^j \le \Delta f_i^{\max} \ ; \ \forall i \in S_{AF}, \ \forall j \end{cases} ;$$

In the next chapter, this generation scheduling formulation with KE is applied to a number of case studies.

Chapter 3. Applications and Results

3.1 Introduction and Data

In this chapter, numerical simulations are performed to assess and compare the performance of the KE storage apparatus whose models were developed in the previous chapters as well as to verify the theoretical derivations and assumptions made.

The simulations perform two types of test for each of the three forms of KE storage, each test being conducted with a different system demand time profile. The two tests are:

(A) Cost and Marginal Price Reduction

This test is intended to demonstrate the advantage of using KE storage apparatus to decrease the energy cost and its marginal price. Fig. 3.1 shows the demand profile used for this test.

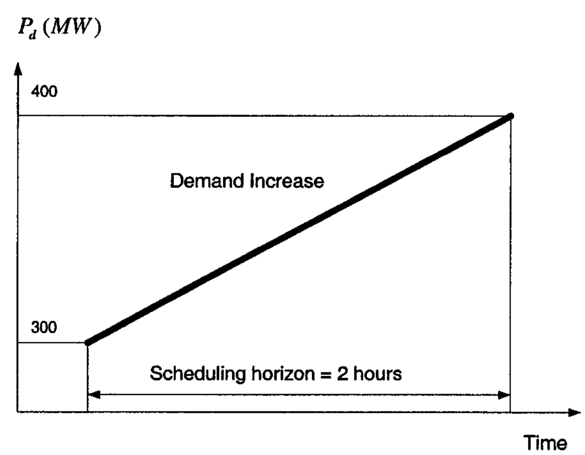

Figure-3.1: *Demand increase profile.*

(B) Congestion Management

This test is intended to demonstrate the advantage of using KE storage apparatus to relieve transmission congestion. Fig. 3.2 shows the demand profile used for this test.

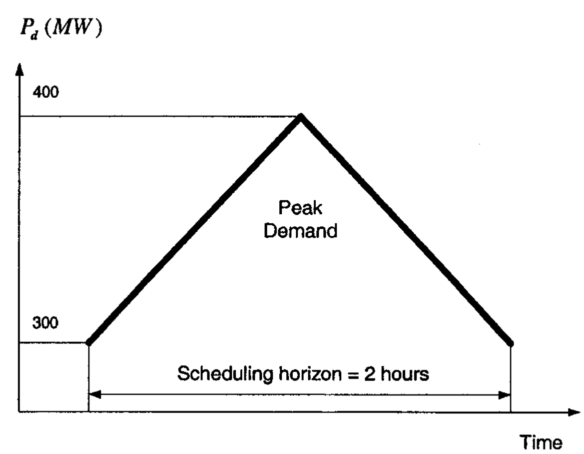

Figure-3.2: *Peak demand profile.*

In all simulations, the optimal scheduling problem is to minimize a cost function subject to inequality and equality constraints as described in the previous chapter. The mathematical software platform used for all simulations is GAMS (General Algebraic Modeling System) [19], which is suitable for solving large mathematical programming problems.

The following is the set of the common data used in all simulations:

Table 3.1: *Basic Data*

System Demand Variation, P_d *[MW]*	300 : 400
Base Voltage, V_b *[KV]*	100
Base Power, S_b *[MVA]*	100
Base Impedance, Z_b *[Ohms]*	100
Synchronous Frequency, f_{syn} *[Hz]*	60
Synch. Frequency Deviation Limits, Δf *[Hz]*	±0.5
Initial Time Error, $T_e(0)$ *[s]*	0
Final Maximum Time Error, ΔT_e^{max} *[s]*	0
Time Step, τ *[s]*	300
Index of Number of Buses, *i*	1 : *n*
Index of Number of Time Steps, *j*	1 : *nt*
Number of Buses, *n*	3
Number of Time Steps, *nt*	24

Table 3.2: *Bus Data*

	Bus-1	Bus-2	Bus-3
Maximum Generation Output, P_g^{max} *[MW]*	200	200	200
Minimum Generation Output, P_g^{min} *[MW]*	0	0	0
Production Fixed Cost, C_0 *[$/h]*	0	0	0
Variable Cost Parameter, *a* *[$/MWh]*	20	60	90
Variable Cost Parameter, *b* *[$/MW²h]*	0.02	0.05	0.08
Generator Droop, *R* *[Hz/MW]*	0.02	0.02	0.02
Load Sensitivity Factor, k_f *[MW/Hz]*	0	0	0
Inertia Constant, *H* *[s]*	5	5	5
Bus Voltage Magnitude, *V* [pu]	1	1	1

Table 3.3: *Line Data*

	Line 1-2	Line 2-3	Line 1-3
Minimum Line Flow, P^{min} *[MW]*	Free	Free	Free
Maximum Line Flow, P^{max} *[MW]*	Free	Free	Free
Line Resistance, *[Ohms/km]*	0	0	0
Line Reactance, *[Ohms/km]*	0.4	0.4	0.4
Line Length, *[km]*	100	100	100

3.2 KE Storage in Synchronous Generators

The three-bus system shown in Fig. 3.3 is used to perform the simulations over a scheduling period of 2 hours with 5-minute time steps.

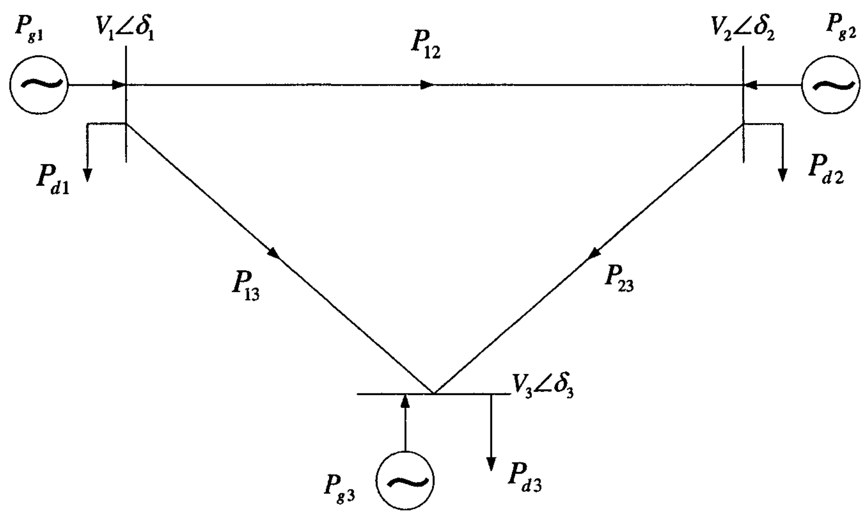

Figure-3.3: *Three-bus system with generators and loads.*

3.2.1 Generation Scheduling Formulation without Flywheels

According to the formulation of the previous chapter, the generation scheduling problem without flywheels can be expressed in the following form:

$$\boxed{\min\left\{C=\sum_{j=1}^{nt}\sum_{i\in S_{SG}}\tau C_i\left(P_{gi}^j\right)\right\}}$$

where,

$$P_{gi}^j = P_{ci}^j - \frac{1}{R_i}\Delta f^j \quad ; \qquad \forall i,j$$

Subject to,

$$KE_i^j = KE_i^{j-1} + \tau\left[P_{gi}^j - P_{di}^j - P_i(\underline{\delta}^j)\right]; \qquad \forall i, j$$

$$KE_i^j = KE_i^{syn}\left[1 + \frac{\Delta f^j}{f_{syn}}\right]^2 ; \qquad \forall i, j$$

$$KE_i^{syn} = H_i S_{Bi} ; \qquad \forall i$$

$$P_{di}^j = \varsigma_i P_{so}^j\left[1 + k_{fi}\Delta f^j\right] ; \qquad \forall i, j$$

$$P_{ik}(\underline{\delta}^j) = \frac{(\delta_i^j - \delta_k^j)}{X_{ik}} ; \qquad \forall i, k, j$$

$$\Delta T_e = \sum_j \left(\frac{\Delta f^j}{f_{syn}}\right)\tau ;$$

$$P_{gi}^{\min} \le P_{gi}^j \le P_{gi}^{max} ; \qquad \forall i, j$$

$$\Delta f^{\min} \le \Delta f^j \le \Delta f^{max} ; \qquad \forall j$$

$$\left|P_{ik}(\underline{\delta}^j)\right| \le P_{ik}^{max} ; \qquad \forall i, k, j$$

$$\left|\Delta T_e\right| \le \Delta T_e^{max} ;$$

3.2.2 Tests Studies

For each of the two types of load profile examined ((A) Steady demand increase; (B) Peak demand), two cases are considered,

I) No system frequency variation (that is, no KE storage);

II) Frequency variation allowed within $\pm 0.5\,Hz$ (with KE storage).

Test (A) Steady demand increase

Here, we focus on the impact of KE storage on cost and marginal cost reduction.

Difference in Costs (With and without KE storage):

	Without KE storage	With KE storage
Costs ($/h)	14,963.33	14,962.76

The difference in costs is trivially small due to the small amount of KE that can be stored and released in the synchronously rotating machines (three generators) for the narrow frequency deviation allowed of $\pm 0.5\,Hz$.

Table 3.4 shows the power demand, power generation as well as the power derived from KE exchanges with the generators throughout the scheduled 24 time steps. It is seen that at some time steps, some KE is absorbed or released. In the Table, three symbols for power are used:

- P_{di}^{j} - represents the demand
- P_{gi}^{j} - represents the power of generation
- P_{KEGi}^{j} represents the power derived over one time step from the KE exchange with the generator, that is, $-\frac{\Delta KE_{Gi}^{j}}{\tau} = \frac{-KE_{Gi}^{j} + KE_{Gi}^{j-1}}{\tau}$;

Table 3.4: *Demand, generator power and power derived from the KE of synchronous generators. Test A, Case II: With KE storage.*

Time Step	P_{d1} (MW)	P_{d2} (MW)	P_{d3} (MW)	P_{g1} (MW)	P_{g2} (MW)	P_{g3} (MW)	P_{KEG1} (MW)	P_{KEG2} (MW)	P_{KEG3} (MW)
1	100	100	104	200	104.15	0	-0.056	-0.056	-0.042
2	100	100	108	200	108	0	0	0	0
3	100	100	112	200	112	0	0	0	0
4	100	100	116	200	116	0	0	0	0
5	100	100	120	200	120	0	0	0	0
6	100	100	124	200	124	0	0	0	0
7	100	100	128	200	128	0	0	0	0
8	100	100	132	200	132	0	0	0	0
9	100	100	136	200	136	0	0	0	0
10	100	100	140	200	140	0	0	0	0
11	100	100	144	200	144	0	0	0	0
12	100	100	148	200	148	0	0	0	0
13	100	100	152	200	152	0	0	0	0
14	100	100	156	200	156	0	0	0	0
15	100	100	160	200	160	0	0	0	0
16	100	100	164	200	164	0	0	0	0
17	100	100	168	200	168	0	0	0	0
18	100	100	172	200	172	0	0	0	0
19	100	100	176	200	176	0	0	0	0
20	100	100	180	200	180	0	0	0	0
21	100	100	184	200	184	0	0	0	0
22	100	100	188	200	188	0	0	0	0
23	100	100	192	200	192	0	0	0	0
24	100	100	196	200	195.69	0	0.111	0.111	0.083

The results of the power derived from the KE of the generators in Table 3.4 are shown graphically in Fig. 3.4.

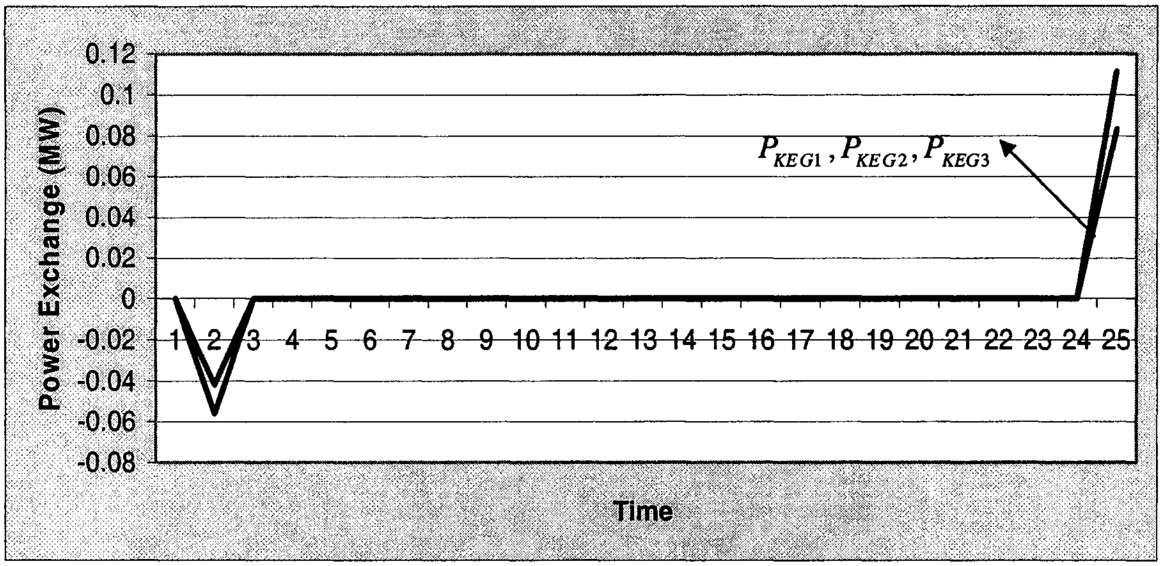

Figure-3.4: *Power from KE of synchronous generators. Test A, Case II: With KE storage.*

Fig. 3.5 shows the prices over the scheduling horizon for both cases (Case I, without frequency deviation, and Case II with frequency deviation). The prices at all buses are the same as there is no line congestion.

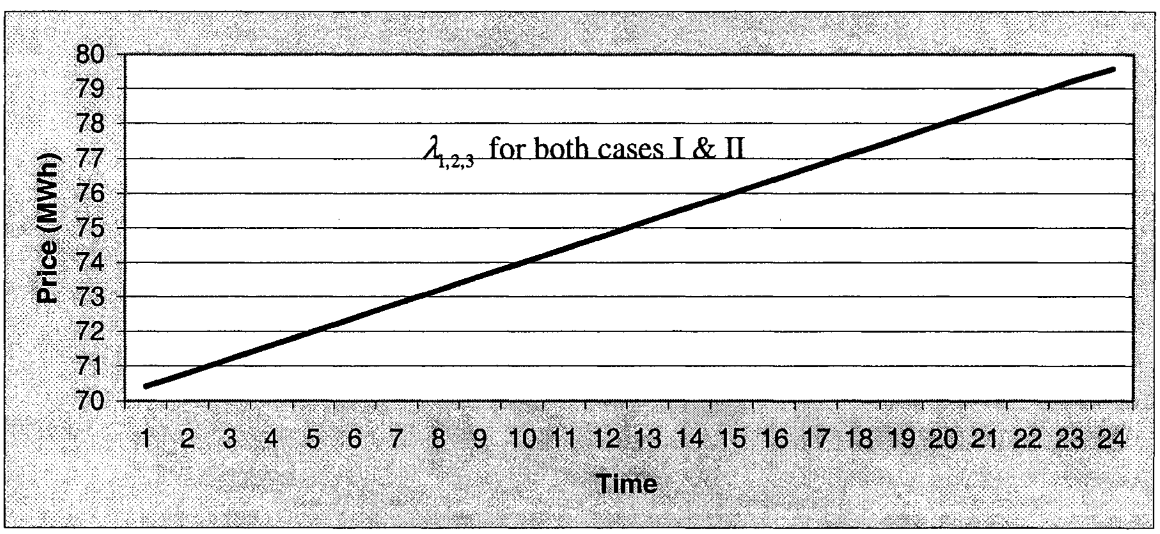

Figure-3.5: *System incremental cost (Price) variation over time. Test A, Cases I and II: Without and with KE storage in synchronous generators only.*

Table 3.5 shows the difference in the prices between the two cases which is very small as the KE storage in the synchronous generators of the system is not sufficiently large.

Table-3.5: *System incremental costs (Prices) variation over time. Test A, Cases I and II: Without and with KE storage in synchronous generators only.*

Time Step	λ_1 (Case-I) (MWh)	λ_2 (Case-I) (MWh)	λ_3 (Case-I) (MWh)	λ_1 (Case-II) (MWh)	λ_2 (Case-II) (MWh)	λ_3 (Case-II) (MWh)
1	70.4	70.4	70.4	70.415	70.415	70.415
2	70.8	70.8	70.8	70.8	70.8	70.8
3	71.2	71.2	71.2	71.2	71.2	71.2
4	71.6	71.6	71.6	71.6	71.6	71.6
5	72	72	72	72	72	72
6	72.4	72.4	72.4	72.4	72.4	72.4
7	72.8	72.8	72.8	72.8	72.8	72.8
8	73.2	73.2	73.2	73.2	73.2	73.2
9	73.6	73.6	73.6	73.6	73.6	73.6
10	74	74	74	74	74	74
11	74.4	74.4	74.4	74.4	74.4	74.4
12	74.8	74.8	74.8	74.8	74.8	74.8
13	75.2	75.2	75.2	75.2	75.2	75.2
14	75.6	75.6	75.6	75.6	75.6	75.6
15	76	76	76	76	76	76
16	76.4	76.4	76.4	76.4	76.4	76.4
17	76.8	76.8	76.8	76.8	76.8	76.8
18	77.2	77.2	77.2	77.2	77.2	77.2
19	77.6	77.6	77.6	77.6	77.6	77.6
20	78	78	78	78	78	78
21	78.4	78.4	78.4	78.4	78.4	78.4
22	78.8	78.8	78.8	78.8	78.8	78.8
23	79.2	79.2	79.2	79.2	79.2	79.2
24	79.6	79.6	79.6	79.569	79.569	79.569

Test (B) Peak demand

Here, we focus on the impact of using the KE storage in the generators to relieve congestion management. For this purpose, the line connecting buses 1 and 3 in the power network is limited to 102 MW.

Table 3.6 shows the demand, power generation, as well as the power derived from KE exchanges with generators during the scheduling period. It is seen that KE energy is stored during low demand periods to be released during high demand periods, when the transmission line is congested.

Table 3.6: *Demand, generator power, and power derived from the KE of synchronous generators. Test B, Case II: With KE storage.*

Time Step	P_{d1} (MW)	P_{d2} (MW)	P_{d3} (MW)	P_{g1} (MW)	P_{g2} (MW)	P_{g3} (MW)	P_{KEG1} (MW)	P_{KEG2} (MW)	P_{KEG3} (MW)
1	100	100	100	200	100.15	0	-0.056	-0.056	-0.042
2	100	100	110	200	110	0	0	0	0
3	100	100	120	200	120	0	0	0	0
4	100	100	130	200	130	0	0	0	0
5	100	100	140	200	140	0	0	0	0
6	100	100	150	200	150	0	0	0	0
7	100	100	160	200	160	0	0	0	0
8	100	100	170	200	170	0	0	0	0
9	100	100	180	200	180	0	0	0	0
10	100	100	190	200	190	0	0	0	0
11	100	100	200	200	200	0	0	0	0
12	100	100	210	200	209.69	0	0.111	0.111	0.083
13	100	100	200	200	200	0	0	0	0
14	100	100	190	200	190	0	0	0	0
15	100	100	180	200	180	0	0	0	0
16	100	100	170	200	170	0	0	0	0
17	100	100	160	200	160	0	0	0	0
18	100	100	150	200	150	0	0	0	0
19	100	100	140	200	140	0	0	0	0
20	100	100	130	200	130	0	0	0	0
21	100	100	120	200	120	0	0	0	0
22	100	100	110	200	110	0	0	0	0
23	100	100	100	200	100	0	0	0	0
24	100	100	90	200	90	0	0	0	0

The results of Table 3.6 are shown graphically in Fig. 3.6.

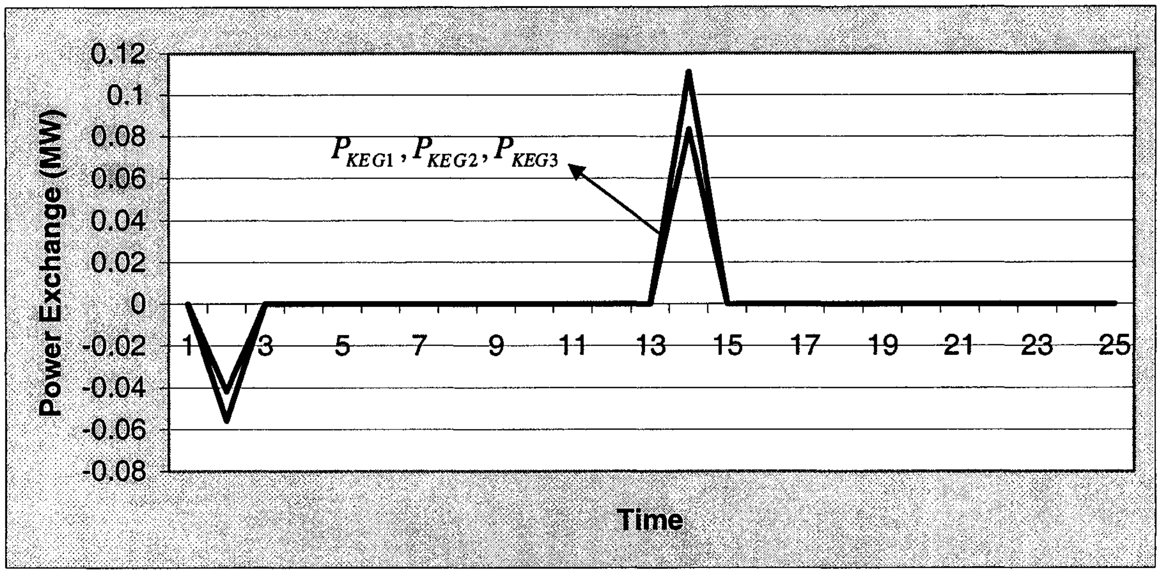

Figure-3.6: *Power from KE of synchronous generators. Test B, Case II: With KE storage.*

Fig. 3.7 shows that the single system price diverges into three different nodal prices during congestion. This Figure applies for both cases I and II. So again, as in Test A, the KE stored only in the rotating masses of the generators is not enough to have a sufficient influence to relieve congestion and unify the IC in all buses. This explains why the case with and without frequency variation are essentially the same.

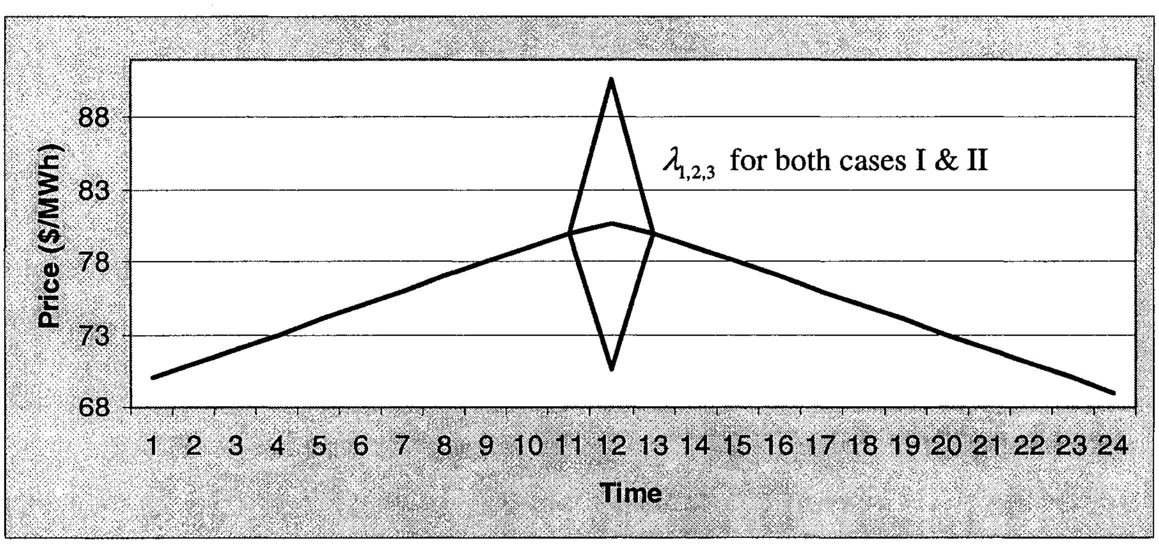

Figure-3.7: *System and bus incremental costs (Prices) variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators only.*

Table 3.7 shows the very small differences in the prices between cases I and II because of the small amount of KE available from the synchronous generators.

Table-3.7: *System and bus incremental costs (Prices) variation over time, Test B, Cases I and II: Without and with KE storage in synchronous generators only.*

Time Step	λ_1 (Case-I) (MWh)	λ_2 (Case-I) (MWh)	λ_3 (Case-I) (MWh)	λ_1 (Case-II) (MWh)	λ_2 (Case-II) (MWh)	λ_3 (Case-II) (MWh)
1	70	70	70	70.015	70.015	70.015
2	71	71	71	71	71	71
3	72	72	72	72	72	72
4	73	73	73	73	73	73
5	74	74	74	74	74	74
6	75	75	75	75	75	75
7	76	76	76	76	76	76
8	77	77	77	77	77	77
9	78	78	78	78	78	78
10	79	79	79	79	79	79
11	80	80	80	79.969	79.969	79.969
12	70.56	80.6	90.64	70.631	80.633	90.636
13	80	80	80	79.969	79.969	79.969
14	79	79	79	79	79	79
15	78	78	78	78	78	78
16	77	77	77	77	77	77
17	76	76	76	76	76	76
18	75	75	75	75	75	75
19	74	74	74	74	74	74
20	73	73	73	73	73	73
21	72	72	72	72	72	72
22	71	71	71	71	71	71
23	70	70	70	70	70	70
24	69	69	69	69	69	69

Table 3.8 shows the power flow variations over the 24 time-steps for the two case-studies. The Table shows that the small amount of KE storage in the synchronous generators of the system is not sufficient to relieve the congestion of line 1-3 at 102 MW at the peak of demand.

Table-3.8: *Power flow variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators only.*

Time Step	P_{12} (Case-I) (MW)	P_{23} (Case-I) (MW)	P_{13} (Case-I) (MW)	P_{12} (Case-II) (MW)	P_{23} (Case-II) (MW)	P_{13} (Case-II) (MW)
1	33.3	33.3	66.7	33	33	66.7
2	30	40	70	30	40	70
3	26.7	46.7	73.3	27	47	73.3
4	23.3	53.3	76.7	23	53	76.7
5	20	60	80	20	60	80
6	16.7	66.7	83.3	17	67	83.3
7	13.3	73.3	86.7	13	73	86.7
8	10	80	90	10	80	90
9	6.7	86.7	93.3	7	87	93.3
10	3.3	93.3	96.7	3	93	96.7
11	0	100	100	0	100	100
12	-2	104	102	-2	104	102
13	0	100	100	0	100	100
14	3.3	93.3	96.7	3	93	96.7
15	6.7	86.7	93.3	7	87	93.3
16	10	80	90	10	80	90
17	13.3	73.3	86.7	13	73	86.7
18	16.7	66.7	83.3	17	67	83.3
19	20	60	80	20	60	80
20	23.3	53.3	76.7	23	53	76.7
21	26.7	46.7	73.3	27	47	73.3
22	30	40	70	30	40	70
23	33.3	33.3	66.7	33	33	66.7
24	36.7	26.7	63.3	37	27	63.3

3.2.3 Case Comparisons and Conclusions

It can be seen from the tests summarized in Figs. 3.4 and 3.6 that the stored KE in the rotating masses of the existing machines in a typical power system is not sufficient to have a significant impact on power system economic or security operational objectives. There is no significant gain in the cost and marginal cost as shown in Fig. 3.5, Tables 3.5 and 3.6. In addition, Fig. 3.8, Tables 3.7 and 3.8 show the insufficiency of the stored KE in synchronous generators to relieve congestion.

Thus, in order to demonstrate the capability of KE storage within a synchronous system to have a significant effect on power system economics and security, we now consider a system with a large number of rotating synchronous flywheels.

3.3 KE Storage in Synchronous Flywheels

Synchronous flywheels are synchronous machines operating at the system frequency and subject to the same narrow range of frequency variation as synchronous generators.

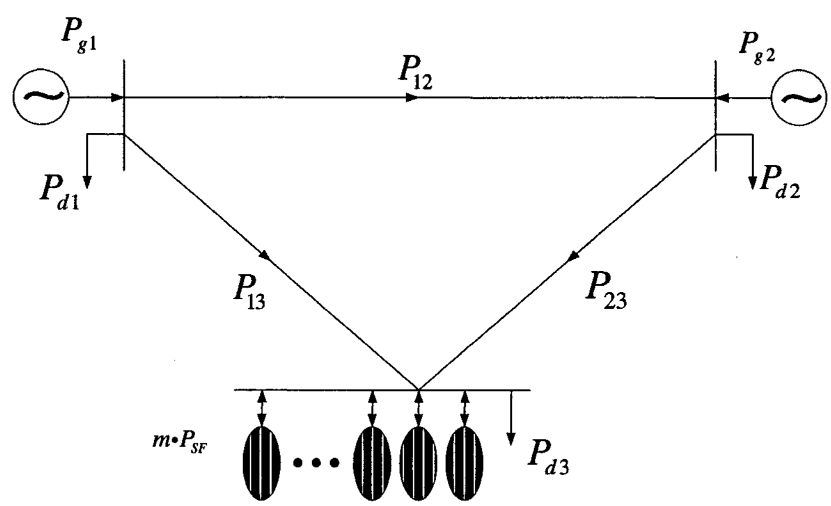

Figure-3.8: *Three bus system with generators, loads and synchronous flywheels.*

3.3.1 Generation Scheduling Formulation with Synchronous Flywheels

According to the formulation of the previous chapter, the scheduling problem with synchronous flywheels can be expressed in the following form:

$$\boxed{\min\left\{C=\sum_{j=1}^{nt}\sum_{i\in S_{SG}}\tau C_i\left(P_{gi}^j\right)\right\}}$$

where,

$$P_{gi}^{j} = P_{ci}^{j} - \frac{1}{R_i}\Delta f^{j} \quad ; \quad \forall i \in S_{SG},\ \forall j$$

Subject to,

$$KE_i^{j} = KE_i^{j-1} + \tau\left[P_{ci}^{j} - \frac{\Delta f^{j}}{R_i} - P_{di}^{j} - P_i(\underline{\delta}^{j})\right]; \quad \forall i \in S_{SG}, \forall j$$

$$KE_i^{j} = KE_i^{j-1} + \tau\left[-\frac{\Delta f^{j}}{R_i} - P_{di}^{j} - P_i(\underline{\delta}^{j})\right]; \quad \forall i \in S_{SF}, \forall j$$

where,

$$KE_i^{j} = KE_i^{syn}\left[1 + \frac{\Delta f^{j}}{f_{syn}}\right]^2 \quad ; \quad \forall i, j$$

$$KE_i^{syn} = H_i S_{Bi} \quad ; \quad \forall i$$

$$P_{di}^{j} = \varsigma_i P_{so}^{j}\left[1 + k_{fi}\Delta f^{j}\right] \quad ; \quad \forall i, j$$

$$P_{ik}(\underline{\delta}^{j}) = \frac{(\delta_i^{j} - \delta_k^{j})}{X_{ik}} \quad ; \quad \forall i, k, j$$

and,

$$\Delta T_e = \sum_j \left(\frac{\Delta f^{j}}{f_{syn}}\right)\tau \quad ;$$

$$P_{gi}^{\min} \le P_{gi}^{j} \le P_{gi}^{max} \quad ; \quad \forall i \in S_{SG},\ \forall j$$

$$-\frac{1}{R_i}\Delta f^{\min} \le P_{gi}^{j} \le -\frac{1}{R_i}\Delta f^{\max} \quad ; \quad \forall i \in S_{SF},\ \forall j$$

$$\Delta f^{\min} \le \Delta f^{j} \le \Delta f^{max} \quad ; \qquad \forall j$$

$$\left|P_{ik}(\underline{\delta}^{j})\right| \le P_{ik}^{max} \quad ; \qquad \forall i,k,j$$

$$\left|\Delta T_{e}\right| \le \ \Delta T_{e}^{max} \quad ;$$

3.3.2 Tests Studies

Again, for each of the two tests examined ((A) Steady demand increase; (B) Peak demand), two cases are considered,

I) No system frequency variation (that is, no KE storage);

II) Frequency variation allowed within $\pm 0.5\,Hz$ (with KE storage).

This system contains the same generator and load data as in Section 3.2, however we have added synchronous flywheel capability to bus 3, as seen in Fig. 3.8. One thousand synchronous flywheels (m = 1000), each rated at 1000 MWs at 60 Hz, are installed in bus 3. The economics of adding synchronous flywheels are not considered at this time, the goal being to demonstrate the capability of storing and exchanging sufficient KE in these devices to have a significant impact on system economics and security.

Test (A) Steady demand increase

Here, we focus on the impact of KE storage on cost and marginal cost reduction.

Costs Difference with and without KE storage:

	With no KE storage	With KE storage
Costs ($/h)	14,963.33	14,816.38

From the above table, we see that with the installed synchronous flywheels, the overall system hourly cost is improved by about 1% when KE exchanges are used in the generation scheduling.

Table 3.9 shows the demand, power generation as well as the power derived from KE exchanges of synchronous generators and flywheels during the scheduling period. The symbol P_{KESFi}^{j} represents the power derived from the KE of synchronous flywheel i at time step j, that is, $-\frac{\Delta KE_{SFi}^{j}}{\tau} = \frac{-KE_{SFi}^{j} + KE_{SFi}^{j-1}}{\tau}$;

The Table clearly demonstrates that the optimum generation schedule stores KE during low demand periods at lower prices to be released during high demand periods at higher prices. This scheduling behavior is logical.

Table 3.9: *Demand, generator power and power derived from the KE of synchronous generators and flywheels. Test A, Case II: With KE storage.*

Time Step	P_{d1} (MW)	P_{d2} (MW)	P_{d3} (MW)	P_{g1} (MW)	P_{g2} (MW)	P_{KEG1} (MW)	P_{KEG2} (MW)	P_{KESF} (MW)
1	100	100	104	200	120.39	-0.022	-0.022	-16.347
2	100	100	108	200	120.39	-0.016	-0.016	-12.357
3	100	100	112	200	120.39	-0.011	-0.011	-8.368
4	100	100	116	200	120.39	-0.006	-0.006	-4.379
5	100	100	120	200	120.39	-0.001	-0.001	-0.389
6	100	100	124	200	124	0	0	0
7	100	100	128	200	128	0	0	0
8	100	100	132	200	132	0	0	0
9	100	100	136	200	136	0	0	0
10	100	100	140	200	140	0	0	0
11	100	100	144	200	144	0	0	0
12	100	100	148	200	148	0	0	0
13	100	100	152	200	152	0	0	0
14	100	100	156	200	156	0	0	0
15	100	100	160	200	160	0	0	0
16	100	100	164	200	164	0	0	0
17	100	100	168	200	168	0	0	0
18	100	100	172	200	172	0	0	0
19	100	100	176	200	172.07	0.005	0.005	3.920
20	100	100	180	200	172.07	0.011	0.011	7.916
21	100	100	184	200	172.07	0.016	0.016	11.910
22	100	100	188	200	172.07	0.021	0.021	15.905
23	100	100	192	200	172.07	0.026	0.026	19.899
24	100	100	196	200	172.07	0.032	0.032	23.894

Fig. 3.9 shows graphically the power exchange with the KE stored in the synchronous flywheels. The power exchange with the KE stored in the generators is also shown in the Figure, but it is extremely small compared to the power derived from the flywheels' KE.

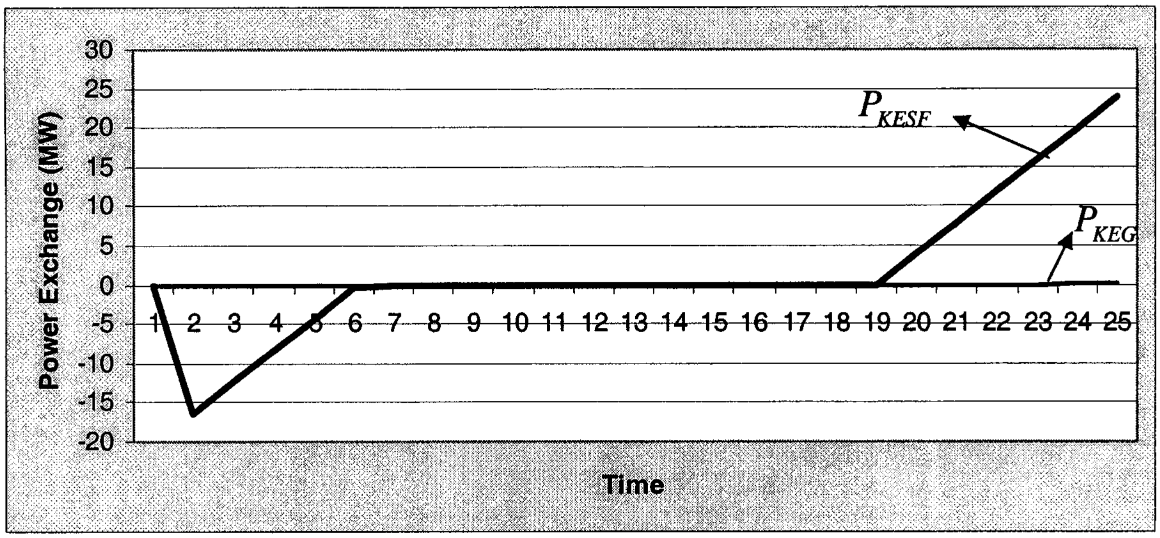

Figure-3.9: *Power from KE of synchronous generators and flywheels. Test A, Case II: With KE storage.*

Fig. 3.10 shows how the use of stored KE affects the system incremental cost (price). We observe that, compared to Case I without KE exchange, in Case II with KE exchange, this price decreases at high demand and high prices, and increases at low demand and low prices.

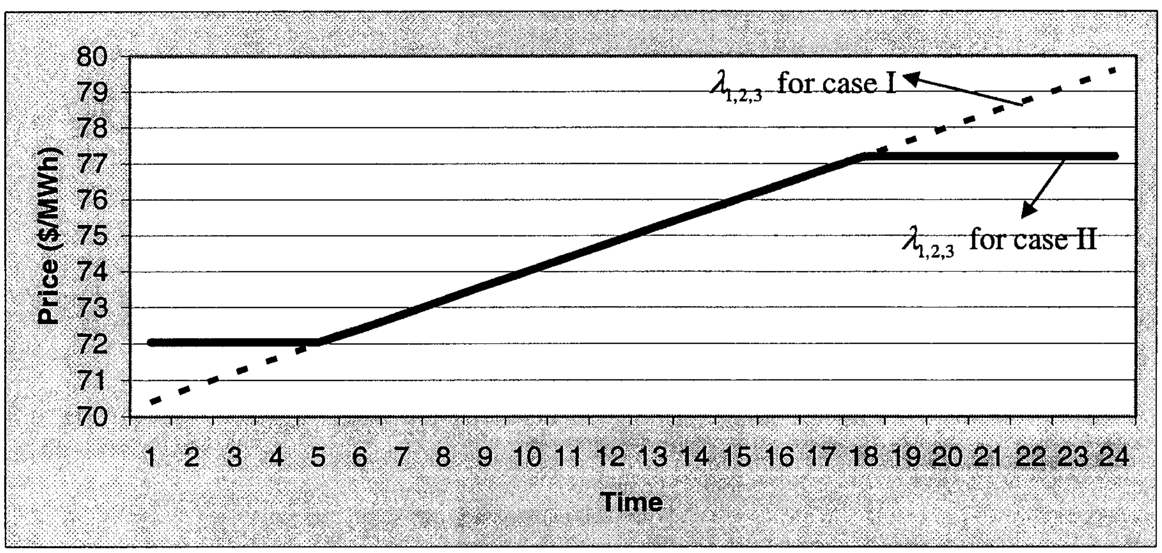

Figure-3.10: *System incremental cost (Price) variation over time. Test A, Cases I and II: Without and with KE storage in synchronous generators and flywheels.*

Test (B) Peak demand

Here, we focus on the impact of KE storage on congestion management.

Table 3.9 shows the demand, power generation as well as the power derived from KE exchanges of synchronous generators and flywheels during the scheduling time period. Again, it is seen that KE energy is stored during low demand periods at the beginning of the scheduling horizon, to be released during the peak demand periods in the middle of the scheduling horizon, thus relieving transmission line congestion.

Table 3.10: *Demand, generator power and power derived from the KE of synchronous generators and flywheels. Test B, Case II: With KE storage.*

Time Step	P_{d1} (MW)	P_{d2} (MW)	P_{d3} (MW)	P_{g1} (MW)	P_{g2} (MW)	P_{KEG1} (MW)	P_{KEG2} (MW)	P_{KEST} (MW)
1	100	100	100	230	93.98	-0.032	-0.032	-23.92
2	100	100	110	230	93.98	-0.019	-0.019	-13.947
3	100	100	120	230	93.98	-0.005	-0.005	-3.973
4	100	100	130	230	100	0	0	0
5	100	100	140	230	110	0	0	0
6	100	100	150	230	120	0	0	0
7	100	100	160	230	130	0	0	0
8	100	100	170	230	140	0	0	0
9	100	100	180	230	150	0	0	0
10	100	100	190	230	151.29	0.012	0.012	8.7
11	100	100	200	230	151.29	0.025	0.025	18.686
12	100	100	210	230	151.29	0.038	0.038	28.673
13	100	100	200	230	151.29	0.025	0.025	18.686
14	100	100	190	230	151.29	0.012	0.012	8.7
15	100	100	180	230	150	0	0	0
16	100	100	170	230	140	0	0	0
17	100	100	160	230	130	0	0	0
18	100	100	150	230	120	0	0	0
19	100	100	140	230	110	0	0	0
20	100	100	130	230	100	0	0	0
21	100	100	120	230	90	0	0	0
22	100	100	110	230	80	0	0	0
23	100	100	100	230	70	0	0	0
24	100	100	90	230	60	0	0	0

Fig. 3.11 shows graphically the power exchanges with the KE in the rotating masses of synchronous generators and flywheels.

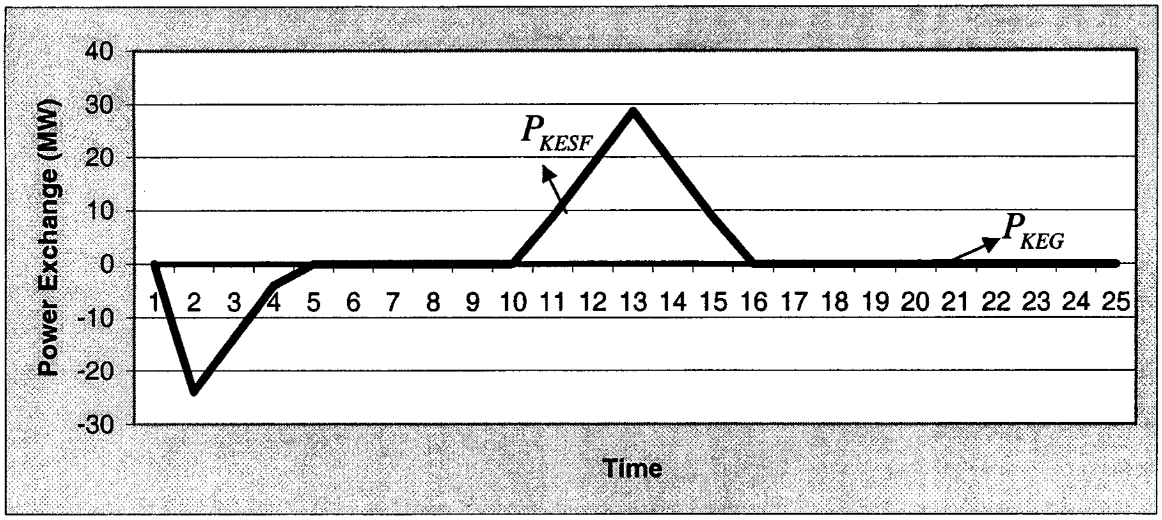

Figure 3.11: *Power from KE of synchronous generators and flywheels. Test B, Case II: With KE storage.*

Fig. 3.12 shows that, when there is no KE exchange, the single system price splits into three different nodal prices during the period of transmission congestion. In the case with KE storage and exchange, there is a single system price over the entire horizon. This means that the KE stored in the rotating masses of the synchronous flywheels is sufficient to relieve congestion.

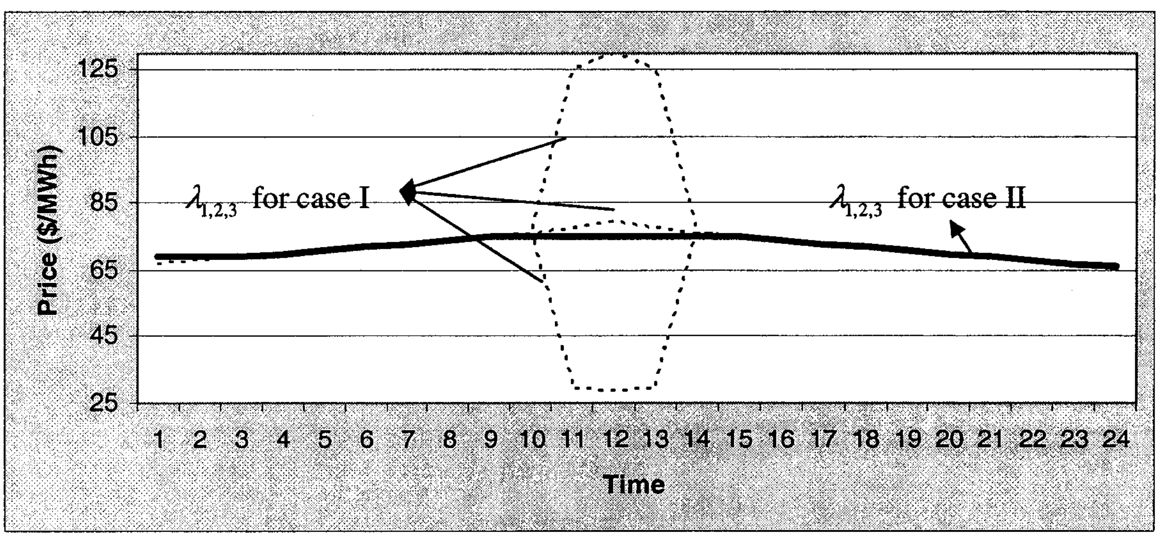

Figure-3.12: *System and bus incremental costs (Prices) variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators and flywheels.*

Table 3.10 shows numerically the difference in prices between the two cases. We notice that for case-I with no KE storage, the nodal prices differ during congestion. In case-II with KE storage, the congestion is relieved and this is reflected by having the same marginal price at all buses. This is highlighted in time steps (11, 12 and 13).

Table-3.11: *System and bus incremental costs (Prices) variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators and flywheels.*

Time Step	λ_1 (Case-I) (MWh)	λ_2 (Case-I) (MWh)	λ_3 (Case-I) (MWh)	λ_1 (Case-II) (MWh)	λ_2 (Case-II) (MWh)	λ_3 (Case-II) (MWh)
1	67	67	67	69.398	69.398	69.398
2	68	68	68	69.398	69.398	69.398
3	69	69	69	69.398	69.398	69.398
4	70	70	70	70	70	70
5	71	71	71	71	71	71
6	72	72	72	72	72	72
7	73	73	73	73	73	73
8	74	74	74	74	74	74
9	75	75	75	75	75	75
10	76	76	76	75.129	75.129	75.129
11	29.08	77.3	125.52	75.129	75.129	75.129
12	28.68	79.3	129.92	75.129	75.129	75.129
13	29.08	77.3	125.52	75.129	75.129	75.129
14	76	76	76	75.129	75.129	75.129
15	75	75	75	75	75	75
16	74	74	74	74	74	74
17	73	73	73	73	73	73
18	72	72	72	72	72	72
19	71	71	71	71	71	71
20	70	70	70	70	70	70
21	69	69	69	69	69	69
22	68	68	68	68	68	68
23	67	67	67	67	67	67
24	66	66	66	66	66	66

Table 3.12 shows the power flow variations over the 24 time-steps for the two case-studies. The Table shows that in the first case without KE storage in the synchronous generators and flywheels, there is congestion in transmission line 1-3 at 109 MW. In the

second case with KE storage in synchronous generators and flywheels, the congestion is relieved.

Table-3.12: *Power flow variation over time. Test B, Cases I and II: Without and with KE storage in synchronous generators and flywheels.*

Time Step	P_{12} (Case-I) (MW)	P_{23} (Case-I) (MW)	P_{13} (Case-I) (MW)	P_{12} (Case-II) (MW)	P_{23} (Case-II) (MW)	P_{13} (Case-II) (MW)
1	53.3	23.3	76.7	45	39.3	84.6
2	50	30	80	45	39.3	84.6
3	46.7	36.7	83.3	45	39.3	84.7
4	43.3	43.3	86.7	43	43.3	86.7
5	40	50	90	40	50	90
6	36.7	56.7	93.3	37	56.7	93.3
7	33.3	63.3	96.7	33	63.3	96.7
8	30	70	100	30	70	100
9	26.7	76.7	103.3	27	76.7	103
10	23.3	83.3	106.7	26	77.5	104
11	18	91	109	26	77.6	104
12	8	101	109	26	77.6	104
13	18	91	109	26	77.6	104
14	23.3	83.3	106.7	26	77.5	104
15	26.7	76.7	103.3	27	76.7	103
16	30	70	100	30	70	100
17	33.3	63.3	96.7	33	63.3	96.7
18	36.7	56.7	93.3	37	56.7	93.3
19	40	50	90	40	50	90
20	43.3	43.3	86.7	43	43.3	86.7
21	46.7	36.7	83.3	47	36.7	83.3
22	50	30	80	50	30	80
23	53.3	23.3	76.7	53	23.3	76.7
24	56.7	16.7	73.3	57	16.7	73.3

3.3.3 Case Comparisons and Conclusions

It has been seen from the tests that the amount of KE stored (10^6 MWs) in the synchronous flywheels and the level of KE exchanged (2% of 10^6 MWs) with the synchronous flywheels is now sufficient to have a significant influence on the security and economics of the system.

We observe in Fig. 3.9 that the power derived from the KE exchange is negative at the beginning of the scheduling time horizon. This means that during this period in which the demand and the prices of electricity are low, KE is being stored in the synchronous generators and flywheels. At the end of the scheduling time horizon, the power derived from the KE becomes positive, meaning that KE is being released at a time when the demand and the price of electricity are high. In the case of peak demand, Fig. 3.11 shows that KE is released in the middle of the scheduling horizon where the peak occurs. The optimization decides the optimal time for storing and releasing KE. Comparing the costs and incremental costs (prices) in Fig. 3.10, we conclude that the economic advantages of using KE storage are significant compared to the case without KE storage. As well, Fig. 3.12 shows that the capability of the stored KE in the synchronous flywheels to relieve congestion is significant.

This section has shown that it is possible to influence power system security and economics through KE storage in synchronous flywheels. However, to achieve the 10^6 MWs of installed flywheel KE, we would need to install a large number of synchronous machines whose cost may be prohibitive. We therefore now consider the installation of asynchronous flywheels having a broad range of rotational speed instead of the 2% possible with synchronous machines.

3.4 KE Storage in Asynchronous Flywheels

To study this alternative, an asynchronous flywheel as an ESA is installed at bus 3 of the 3-bus system shown in Fig. 3.13.

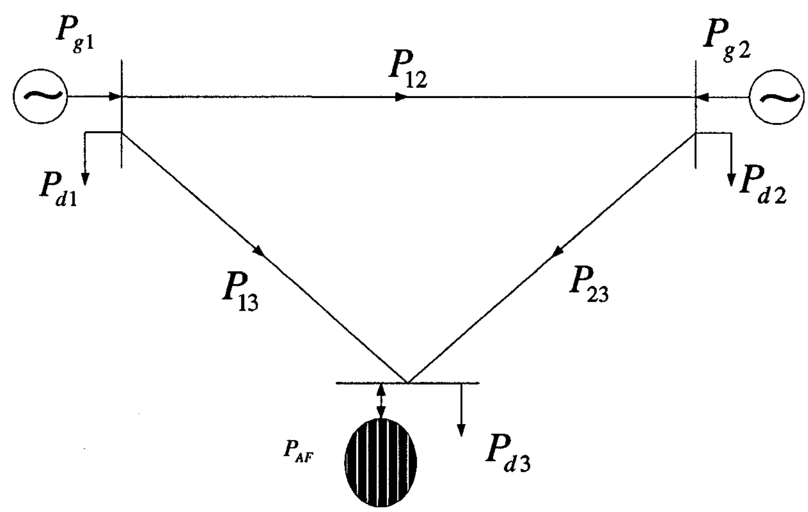

Figure-3.13: *Three bus system with generators, loads and asynchronous flywheel*

3.4.1 Generation Scheduling Formulation with Asynchronous Flywheels

Based on the modeling and formulation presented in the previous sections, the scheduling problem with asynchronous flywheels can be expressed in the following form:

$$\boxed{\min\left\{C=\sum_{j=1}^{nt}\sum_{i\in S_{SG}}\tau C_i\left(P_{gi}^j\right)\right\}}$$

where,

$$P_{gi}^j = P_{ci}^j - \frac{1}{R_i}\Delta f^j \quad ; \qquad \forall i \in S_{SG},\ \forall j$$

Subject to,

$$KE_i^j = KE_i^{j-1} + \tau\left[P_{ci}^j - \frac{\Delta f^j}{R_i} - P_{di}^j - P_i(\underline{\delta}^j)\right]; \quad \forall i \in S_{SG}, \forall j$$

$$KE_i^j = KE_i^{j-1} + \tau\left[-P_{di}^j - P_i(\underline{\delta}^j)\right]; \quad \forall i \in S_{AF}, \forall j$$

$$KE_i^j = KE_i^{syn}\left[1 + \frac{\Delta f^j}{f_{syn}}\right]^2 ; \quad \forall i \in S_{SG}, \forall j$$

$$KE_i^j = KE_i^{syn}\left[1 + \frac{\Delta f_i^j}{f_{syn}}\right]^2 ; \quad \forall i \in S_{AF}, \forall j$$

$$P_{di}^j = \varsigma_i P_{so}^j\left[1 + k_{fi}\Delta f^j\right] ; \quad \forall i, j$$

$$P_{ik}(\underline{\delta}^j) = \frac{(\underline{\delta}_i^j - \underline{\delta}_k^j)}{X_{ik}} ; \quad \forall i, k, j$$

$$\Delta T_e = \sum_j \left(\frac{\Delta f^j}{f_{syn}}\right)\tau ;$$

$$P_{gi}^{\min} \le P_{gi}^j \le P_{gi}^{max} ; \quad \forall i \in S_{SG}, \forall j$$

$$\Delta f^{\min} \le \Delta f^j \le \Delta f^{max} ; \quad \forall j$$

$$\Delta f_i^{\min} \le \Delta f_i^j \le \Delta f_i^{\max} ; \quad \forall i \in S_{AF}, \forall j$$

$$\left|P_{ik}(\underline{\delta}^j)\right| \le P_{ik}^{max} ; \quad \forall i, k, j$$

$$\left|\Delta T_e\right| \le \Delta T_e^{max} ;$$

3.4.2 Tests Studies

The comparison for asynchronous flywheels application in both tests is done between two cases:

I) Without asynchronous flywheel;

II) With asynchronous flywheel.

Again, this system contains the same generator and load data as in the previous sections; however as seen in Fig. 3.13, at bus 3 we have added an asynchronous flywheel rated at speeds varying between 0 Hz and 1651 Hz, and corresponding levels of stored KE between 0 and 0.6×10^6 MWs.

The goal here is to demonstrate the capability of storing and exchanging sufficient KE in this asynchronous device to have a significant impact on system economics and security.

In the tests that follow, the initial speed and KE of the flywheel at the beginning of the scheduling period is assumed to be zero.

Test (A) Steady demand increase

Here, we focus on the impact of KE storage on cost and marginal cost reduction.

Costs difference for case-I without asynchronous flywheel and case-II with asynchronous flywheel:

	Without Asynchronous Flywheel	With Asynchronous Flywheel
Costs ($/h)	14,962.76	14,845.01

Table 3.13 shows the demand, power generation as well as the power derived from KE exchanges with the asynchronous flywheel and synchronous generators during the scheduling period. It is seen how KE energy is stored during low demand periods to be

released during high demand periods. We have defined P^j_{KEAF} as the power derived from the KE exchange of the asynchronous flywheel, that is, $-\frac{\Delta KE^j_{AFi}}{\tau} = \frac{-KE^j_{AFi} + KE^{j-1}_{AFi}}{\tau}$.

Table 3.13: *Demand, generator power and power derived from the KE of synchronous generators and asynchronous flywheel. Test A, Case II: With asynchronous flywheel.*

Time Step	P_{d1} (MW)	P_{d2} (MW)	P_{d3} (MW)	P_{g1} (MW)	P_{g2} (MW)	P_{KEG1} (MW)	P_{KEG2} (MW)	P_{KEAF} (MW)
1	100	100	104	200	118.4	-0.024	-0.024	-14.348
2	100	100	108	200	118.4	-0.017	-0.017	-10.361
3	100	100	112	200	118.4	-0.011	-0.011	-6.375
4	100	100	116	200	118.4	-0.004	-0.004	-2.388
5	100	100	120	200	120	0	0	0
6	100	100	124	200	124	0	0	0
7	100	100	128	200	128	0	0	0
8	100	100	132	200	132	0	0	0
9	100	100	136	200	136	0	0	0
10	100	100	140	200	140	0	0	0
11	100	100	144	200	144	0	0	0
12	100	100	148	200	148	0	0	0
13	100	100	152	200	152	0	0	0
14	100	100	156	200	156	0	0	0
15	100	100	160	200	160	0	0	0
16	100	100	164	200	164	0	0	0
17	100	100	168	200	168	0	0	0
18	100	100	172	200	172	0	0	0
19	100	100	176	200	174.85	0.002	0.002	1.146
20	100	100	180	200	174.85	0.009	0.009	5.14
21	100	100	184	200	174.85	0.015	0.015	9.133
22	100	100	188	200	174.85	0.022	0.022	13.126
23	100	100	192	200	174.85	0.028	0.028	17.119
24	100	100	196	200	174.85	0.035	0.035	21.113

Fig. 3.14 shows graphically the power exchange with the KE stored in the asynchronous flywheel, as well as the power exchange with the KE stored in generators, which is extremely small compared to the amount from the asynchronous flywheel.

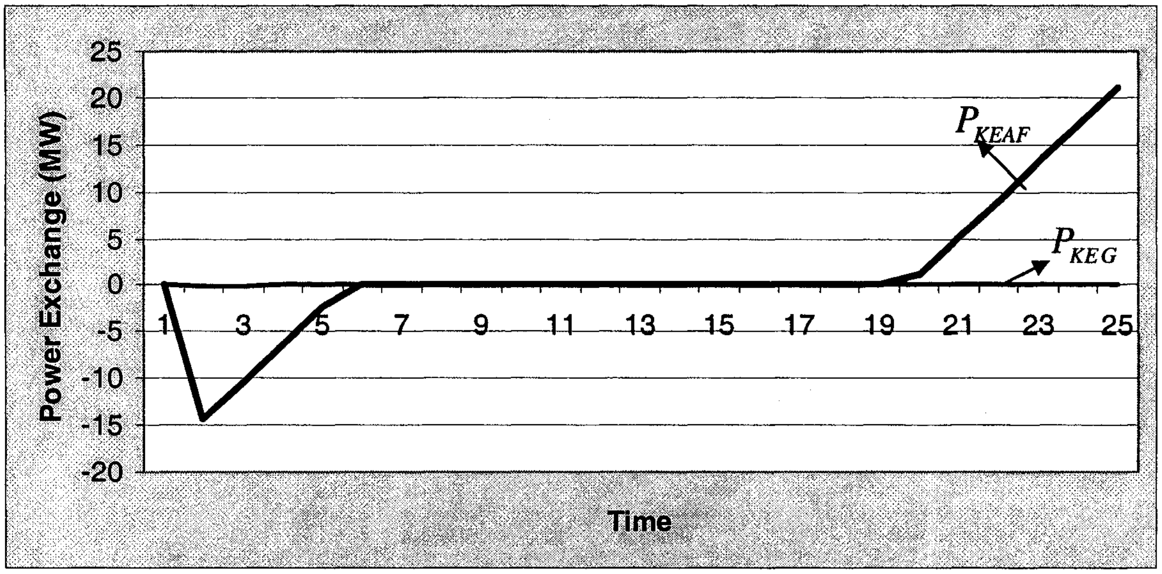

Figure-3.14: *Power from KE of synchronous generators and asynchronous flywheel. Test A, Case II: With asynchronous flywheel.*

Fig. 3.15 shows how the use of stored KE affects the system incremental cost (price). We observe that, compared to Case I without KE exchange, in Case II with KE exchange, this price decreases at high demand and high prices, and increases at low demand and low prices.

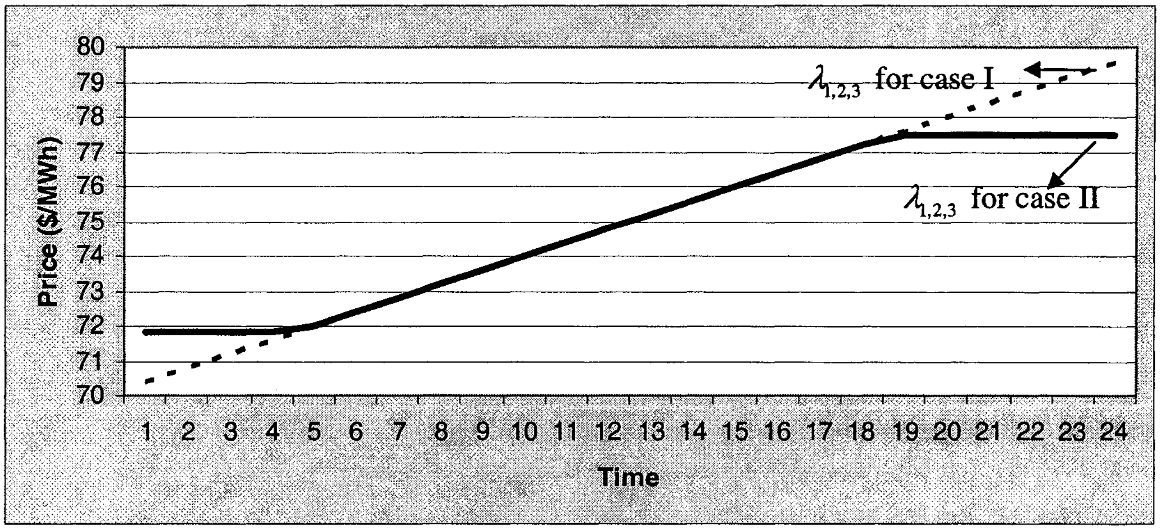

Figure-3.15: *System incremental cost (Price) variation over time. Test A, Cases I and II: Without and with asynchronous flywheel. KE storage in synchronous generators and asynchronous flywheel.*

Test (B) Peak demand

Here, we focus on the impact of KE storage on congestion management.

Table 3.14 shows the demand, power generation as well as the power derived from KE exchanges of synchronous generators and asynchronous flywheel during the scheduling time horizon. Again, it is seen that KE energy is stored during low demand periods at the beginning of the scheduling horizon, to be released during the peak demand periods in the middle of the scheduling horizon, thus relieving transmission line congestion.

Table 3.14: *Demand, generator power and power derived from the KE of synchronous generators and asynchronous flywheel. Test B, Case II: With asynchronous flywheel.*

Time Step	P_{d1} (MW)	P_{d2} (MW)	P_{d3} (MW)	P_{g1} (MW)	P_{g2} (MW)	P_{KEG1} (MW)	P_{KEG2} (MW)	P_{KEAF} (MW)
1	100	100	100	230	91.19	-0.035	-0.035	-21.124
2	100	100	110	230	91.19	-0.019	-0.019	-11.157
3	100	100	120	230	91.19	-0.002	-0.002	-1.191
4	100	100	130	230	100	0	0	0
5	100	100	140	230	110	0	0	0
6	100	100	150	230	120	0	0	0
7	100	100	160	230	130	0	0	0
8	100	100	170	230	140	0	0	0
9	100	100	180	230	150	0	0	0
10	100	100	190	230	154.62	0.009	0.009	5.369
11	100	100	200	230	154.62	0.026	0.026	15.353
12	100	100	210	230	154.62	0.042	0.042	25.335
13	100	100	200	230	154.62	0.026	0.026	15.353
14	100	100	190	230	154.62	0.009	0.009	5.369
15	100	100	180	230	150	0	0	0
16	100	100	170	230	140	0	0	0
17	100	100	160	230	130	0	0	0
18	100	100	150	230	120	0	0	0
19	100	100	140	230	110	0	0	0
20	100	100	130	230	100	0	0	0
21	100	100	120	230	90	0	0	0
22	100	100	110	230	80	0	0	0
23	100	100	100	230	70	0	0	0
24	100	100	90	230	60	0	0	0

Fig. 3.16 shows graphically the variation of power exchanges with the KE stored and released in the rotating mass of the asynchronous flywheel and synchronous generators.

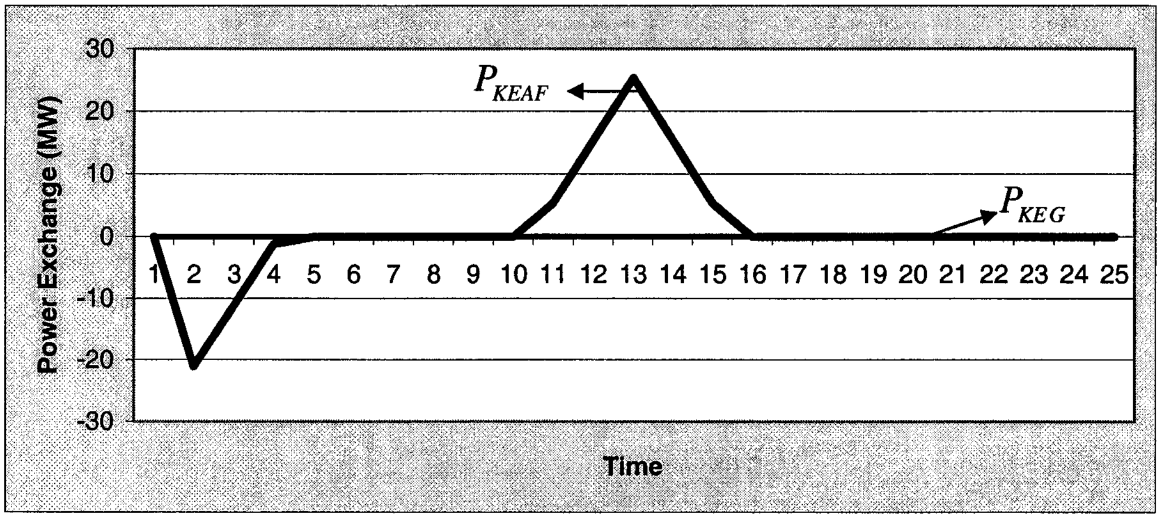

Figure 3.16: *Power from KE of synchronous generators and asynchronous flywheel. Test B, Case II: With asynchronous flywheel.*

Fig. 3.17 shows that, when there is no KE exchange with the asynchronous flywheel, the single system price splits into three different nodal prices during the period of transmission congestion. In the case with KE storage and exchange with the asynchronous flywheel, there is a single system price over the entire horizon. This means that the KE stored in the rotating masses of the asynchronous flywheel is sufficient to relieve congestion.

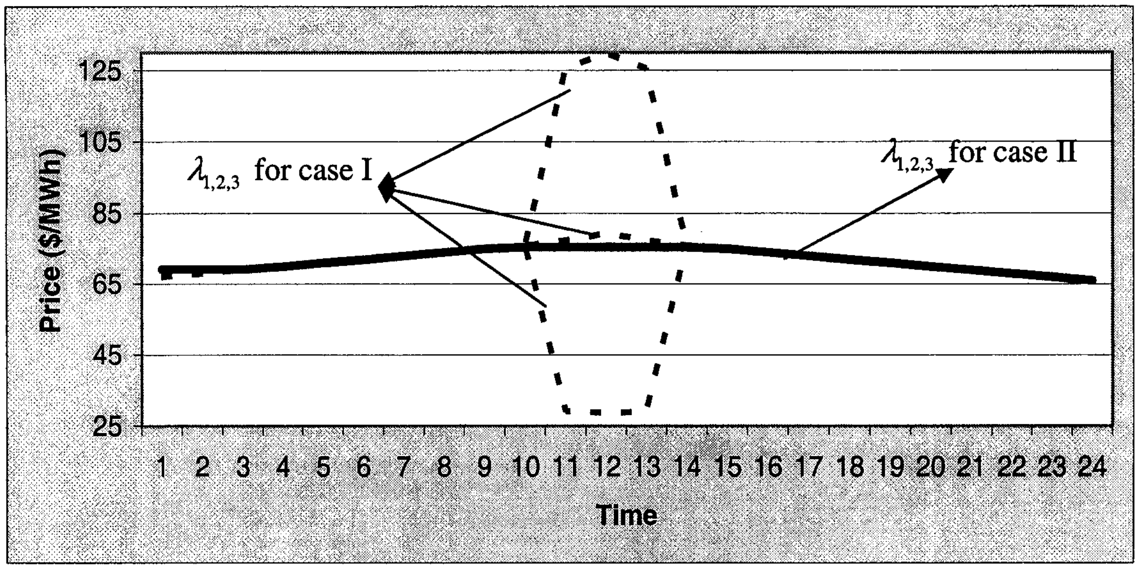

Figure-3.17: *System and bus incremental costs(Prices) variation over time. Test B, Cases I and II: Without and with asynchronous flywheel. KE storage in synchronous generators and asynchronous flywheel.*

Table 3.15 shows numerically the difference in prices between the two cases. We notice that for case-I with no KE storage in the asynchronous flywheel, the nodal prices differ during congestion. In case-II with KE storage in the asynchronous flywheel, the congestion is relieved and this is reflected by having the same price at all buses. This is highlighted in time steps (11, 12 and 13).

Table-3.15: *System and bus incremental costs (Prices) variation over time. Test B, Cases I and II: Without and with asynchronous flywheel. KE storage in synchronous generators and asynchronous flywheel*

Time Step	λ_1 (Case-I) (MWh)	λ_2 (Case-I) (MWh)	λ_3 (Case-I) (MWh)	λ_1 (Case-II) (MWh)	λ_2 (Case-II) (MWh)	λ_3 (Case-II) (MWh)
1	67.015	67.015	67.015	69.119	69.119	69.119
2	68	68	68	69.119	69.119	69.119
3	69	69	69	69.119	69.119	69.119
4	70	70	70	70	70	70
5	71	71	71	71	71	71
6	72	72	72	72	72	72
7	73	73	73	73	73	73
8	74	74	74	74	74	74
9	75	75	75	75	75	75
10	75.969	75.969	75.969	75.462	75.462	75.462
11	29.081	77.328	125.574	75.462	75.462	75.462
12	28.679	79.272	129.866	75.462	75.462	75.462
13	29.081	77.328	125.574	75.462	75.462	75.462
14	75.969	75.969	75.969	75.462	75.462	75.462
15	75	75	75	75	75	75
16	74	74	74	74	74	74
17	73	73	73	73	73	73
18	72	72	72	72	72	72
19	71	71	71	71	71	71
20	70	70	70	70	70	70
21	69	69	69	69	69	69
22	68	68	68	68	68	68
23	67	67	67	67	67	67
24	66	66	66	66	66	66

Table 3.16 shows the power flow variations over the 24 time-steps for the two case-studies. The Table shows that in the first case without KE storage in asynchronous flywheel, there is congestion in the transmission line 1-3 at 109 MW. In the second case with KE storage in asynchronous flywheel, the congestion is relieved.

Table-3.16: *Power flow variation over time. Test B, Cases I and II: Without and with asynchronous flywheel. KE storage in synchronous generators and asynchronous flywheel.*

Time Step	P_{12} (Case-I) (MW)	P_{23} (Case-I) (MW)	P_{13} (Case-I) (MW)	P_{12} (Case-II) (MW)	P_{23} (Case-II) (MW)	P_{13} (Case-II) (MW)
1	53.3	23.4	76.7	46	37.4	83.7
2	50	30	80	46	37.4	83.7
3	46.7	36.7	83.3	46	37.5	83.7
4	43.3	43.3	86.7	43	43.3	86.7
5	40	50	90	40	50	90
6	36.7	56.7	93.3	37	56.7	93.3
7	33.3	63.3	96.7	33	63.3	96.7
8	30	70	100	30	70	100
9	26.7	76.7	103.3	27	76.7	103
10	23.4	83.2	106.7	25	79.8	105
11	17.9	91.1	109	25	79.8	105
12	8.1	100.9	109	25	79.8	105
13	17.9	91.1	109	25	79.8	105
14	23.4	83.2	106.7	25	79.8	105
15	26.7	76.7	103.3	27	76.7	103
16	30	70	100	30	70	100
17	33.3	63.3	96.7	33	63.3	96.7
18	36.7	56.7	93.3	37	56.7	93.3
19	40	50	90	40	50	90
20	43.3	43.3	86.7	43	43.3	86.7
21	46.7	36.7	83.3	47	36.7	83.3
22	50	30	80	50	30	80
23	53.3	23.3	76.7	53	23.3	76.7
24	56.7	16.7	73.3	57	16.7	73.3

3.4.3 Case Comparisons and Conclusions

We conclude from the tests that the specified amount of KE storage in the asynchronous flywheel is sufficient to meet the economic and security goals.

Again, with the KE stored in and exchanged with the asynchronous flywheel, we observed in Fig. 3.14 that the power derived from the KE exchange is negative at the beginning of the scheduling time horizon, identifying this as a period of KE storage that takes advantage of the low prices under low demand. During the last few time steps of the scheduling horizon, the power derived from the KE becomes positive, meaning that

KE is released to take advantage of the high prices during the period of high demand. Fig. 3.16 leads to a similar observation, but here the release of KE happens in the middle of the scheduling horizon to coincide with the peak demand. In all cases, the optimization method decides when to store and release KE in order to minimize the overall cost.

The difference between asynchronous and synchronous flywheels is that the former can store much more KE in accordance with its much wider range of frequency variation, and fewer such devices would be needed compared to the case with synchronous flywheels.

3.5 KE Storage and Exchange for Emergency Fast Reserve Applications

Another application of the use of KE storage is as a source of fast reserve in case of a contingency where a generator is tripped off. Typically, what happens then is that the frequency deviation, Δf, begins to drop, causing the primary regulation in the healthy units to increase their output.

Security requirements dictate that in the event of losing any single generator, the frequency deviation should not exceed a specified limit, e.g. 0.5 Hz. Assuming that network congestion is not active, the power balance before the loss of a generator must satisfy,

$$\sum_i P_{gi} = P_d \tag{3.1}$$

where P_{gi} is the set point of generator i. We assume that at these set points, the system frequency is at its normal level, or equivalently that the frequency deviation, $\Delta f = 0$.

After the loss of generator l, the primary regulation is activated, and if the system is stable, without KE storage and exchange, after about 10 seconds, the system settles to a new steady-state given by,

$$\sum_{i \neq l} (P_{gi} - \frac{\Delta f_l}{R_i}) = P_d \tag{3.2}$$

where Δf_l is the frequency deviation from normal about 10 seconds after the loss of generator l.

Thus, security requires that for all l, $|\Delta f_l| \leq \Delta f^{\max}$; (3.3)

With KE storage and exchange, after the loss of generator l, again, after about 10 seconds, the system settles to a new steady-state given by,

$$\sum_{i \neq l} (P_{gi} - \frac{\Delta f_l}{R_i}) = P_d + \frac{\sum_{i \neq l} \Delta KE_i}{\tau} \tag{3.4}$$

where $\tau = 10\,s$ and,

$$\Delta KE_i = KE_i - KE_i^{syn} \tag{3.5}$$

and where,

$$KE_i = KE_i^{syn} (1 + \frac{\Delta f_l}{f_{syn}})^2 \quad ; \tag{3.6}$$

But, since the frequency deviation is small,

$$\Delta KE_i \simeq 2 KE_i^{syn} \frac{\Delta f_l}{f_{syn}} \quad ; \tag{3.7}$$

Substituting (3.7) into (3.4) and rearranging gives,

$$\sum_{i \neq l} (P_{gi} - \frac{\Delta f_l}{R_i} - \frac{2KE_i^{syn} \frac{\Delta f_l}{f_{syn}}}{\tau}) = P_d \quad ; \quad (3.8)$$

Note that (3.8) is valid over the first 10 seconds after the outage only and defines an average frequency deviation over that initial period.

What is shown next is that if we account for the KE release during the transient phase after the loss of a generator, as given in (3.8), the amount of fast reserve needed is not as large as if we do not account for this KE effect, as in (3.2).

Example:

Consider a system with 20 synchronous generating units and a total demand, P_d =1500 MW. Each unit has a capacity of 200 MW (also equal to the power base for each unit, S_{Bi}) and an inertia constant of H_i=8 s. The unit generation costs are linear in their output with constant incremental costs respectively equal to, 10, 20, ... 200 $/MWh for units 1,2, ... 20. The frequency regulation parameter for each unit is $R_i=0.02$ Hz/MW.

From these data, the KE stored in each rotating unit at synchronous speed is H_iS_{Bi} = $8\times200 = 1600$ MWs.

For the demand of 1500 MW, let us schedule-on only units 1,...,9, with all others off. The minimum cost dispatch then puts generators 1 to 7 at their maximum limit, that is, with $P_{gi}=200$ MW for $i=1,...,7$ and $P_{g8}=100$ MW. Let unit 9 be on as reserve but producing zero output. At this pre-contingency state, the power balances and $\Delta f = 0$.

With this schedule, if we lose any of the generators that are scheduled off, nothing happens, since they are producing zero output. Similarly, if we lose generator 9 nothing happens. However, if we lose any one of generators 1 to 7, then generator 8 and the reserve generator 9 begin to supply steady power through its frequency regulation and, for the first ten seconds, through the KE exchange. If we lose generator 8, then only generator 9 will provide power through its frequency regulation. However, in all cases, for the first 10 seconds all generators will supply power from KE exchange.

The logical assumption is that the secondary and tertiary generation control is too slow to act during the first 10 seconds, during which time all generation set points remain constant.

Thus, if we allow the frequency to drop by its maximum 0.5 Hz, the power that can be extracted from the KE stored in each of the scheduled-on generators, within the transient phase of 10 s, is,

$$P_{KEi} = \frac{2KE_i^{syn}\frac{\Delta f}{f_{syn}}}{\tau} = \frac{2(H_i S_{Bi})\frac{\Delta f}{f_{syn}}}{\tau}$$

$$= \frac{2(8\times 200)\frac{0.5}{60}}{10\,s}$$

$$= \frac{3200\frac{0.5}{60}}{10\,s} = 26.67\,MW\ for\,10\,s$$

In our case, we have nine generators scheduled-on, so that after losing one, we can extract eight times this KE, that is,

$$\sum_{i=8} P_{KEi} = 26.67\times 8 = 213.36\,MW\ for\,10s\quad ; \qquad (3.9)$$

To this amount of generating power extracted from the KE, we can add the regulation components provided by generator 9 and possibly by generator 8 (if 8 is not the one lost), since these two generators operate below their maximum of 200 MW. If the frequency is allowed to drop by 0.5 Hz, the regulation terms provided by generators 8 and 9 could be $-\frac{\Delta f}{R_i} = -\frac{-0.5}{0.02} = 25\,MW$.

From (3.9), we can conclude that with 8 scheduled on generators and one reserve, after the loss of any single generator, there is enough power available in the KE of the remaining rotating masses to balance the load over the first ten seconds. In fact, if we also consider the 25 MW of regulating power from the reserve generator, we would have enough fast reserve by scheduling 7 generators with one reserve.

What is important, is that if our model does not consider KE exchange over the first ten seconds, then we would have to schedule 7 more reserve generators producing zero output to be able to supply the necessary power from the regulating components only.

We emphasize that the power from KE exchange is only temporary, that is, it is available only during the transient (about ten seconds) following a contingency. Thus, it is necessary for the secondary control to begin to increase the set point after this transient interval so that the power can continue to be balanced.

Chapter 4: Conclusions and Recommendations

4.1 Conclusions

Kinetic energy (KE) storage systems have been analyzed as an energy storage technology to be integrated into power system operation with the goal of reducing operational costs, attenuating nodal price spikes, and relieving network congestion.

Two types of system demand variation (steady increase and peak demand) have been examined to show the relative effectiveness of KE storage systems.

The motivation behind choosing this type of energy storage system was because power systems have been traditionally equipped to be able to change the rotor speed of generators providing an efficient, reliable mechanism for storing and withdrawing energy. The normal use of the stored KE is to correct accumulated frequency deviations, which manifests itself as a time error on electric clocks. The idea here however was to deploy this naturally available capability as a mechanism for releasing/absorbing KE to/from the power system.

This thesis shows that the available amounts of KE storage in typical synchronous power systems could be enough to provide fast reserve after events where short bursts of energy are needed, such the sudden loss of a generator. In addition, this type of KE storage can serve to perform time error correction. However, the amount of KE stored in the rotating masses of generators and motors in a typical power system is not enough to reduce the energy cost or to relieve network congestion in a significant way.

Synchronous flywheels were also considered in this thesis to investigate whether this form of KE storage would be able to significantly influence system operation. This investigation only looked at technical feasibility without accounting for the cost of installing flywheels. The conclusions with respect to synchronous flywheels are the same as those reached for synchronous machines. Essentially, the range of allowed frequency deviation in a synchronous system, typically less than ± 0.5 Hz, is too small to permit the storage and release of sufficient amounts of energy other than for short bursts lasting less than 10 seconds. This is useful as a source of fast reserve, but it cannot produce steady levels of power lasting for periods of around one hour, quantities that would be required to have a significant impact on power system economics and security.

The use of asynchronous flywheels with a much broader range of frequency deviation is more promising however. From the results of chapter-3, one can conclude that significant overall cost reduction can be achieved by borrowing energy from the stored KE when the prices are high and by restoring the KE when the prices are low. The results also show that congestion management based on the optimum utilization of stored KE can relieve transmission line congestion and attenuate nodal price volatility during peak demand periods.

4.2 Recommendations

Future studies should examine both the technical potential and the costs of asynchronous flywheels, including losses. There are two types of losses: 1) Internal that take place inside the flywheel due to friction of the masses rotating at a very high speed; 2) External losses that take place within power electronic energy conversion devices.

A technical and cost comparison could be done between asynchronous flywheels and other types of energy storage technologies.

Operationally, one can view the use of stored kinetic energy as a distributed generation system (DG) with the following characteristics:

- It is brought on line only when the energy price exceeds a pre-set incremental price cap;
- It can operate both in generating and motoring modes;
- It can be dispatched as a normal generator within its generation range, based on the market-clearing rules;

- The set point of this DG is realized directly by the AGC software at the control centre, as opposed to being transmitted to the generators' power plants;
- The capacity of this DG is given by a frequency band, defined by the power utility (or the market), around the standard system reference frequency;

Once the DG reaches its capacity limit (i.e. the maximum allowable frequency deviation), it can no longer maintain the system incremental cost at the price cap. Nevertheless, it would still be able to reduce the system incremental cost by supplying part of the required generation. When the system incremental cost falls below the set incremental price cap, the DG is turned off. At this time, one has to have an accurate amount of the total energy supplied by the DG to the market.

A market-clearing program and an AGC program could be developed to simulate a combination of load-frequency control (LFC) and energy market auction for an isolated power system. The power system can be assumed to have a number of generating units, some of which will be assigned price curves that will be very expensive to operate around their maximum generation range. The short-term system demand profile can be assumed to be available and defined such that, in the absence of the DG, its peak values lead to major price spikes. Also, to increase price instability, on a weekly basis, some generators could be chosen at random to go on maintenance.

Finally, a future extension of this work is to analyze in more detail how to use stored KE as a fast reserve in primary frequency regulation following the loss of a generating unit.

References

[1] Olle I. Elgerd, Electric Energy Systems Theory: An Introduction, 2nd Edition, McGraw-Hill, Inc. 1971.

[2] J.D. Glover, M. Sarma, Power System Analysis and Design, 3rd Edition, Brooks/Cole, 2002.

[3] James A. Momoh, Electric Power System Applications of Optimization, Marcel Dekker, Inc. 2001.

[4] Arthur R. Bergen, Vijay Vittal, Power System Analysis, 2nd Edition, Prentice-Hall, Inc. 2000.

[5] Vincent Del Toro, Electric Power Systems, Prentice-Hall, Inc. 1992.

[6] N. Jaleeli, L.S. VanSlyck, D.N. Ewart, L.H. Fink, A.G. Hoffman, "Understanding Automatic Generation Control", Transaction on Power Systems, Vol. 7, No. 3, August 1992.

[7] Khadim Hussain, "Control Performance Analysis of Interconnected Power Systems", IEEE Computer Application in Power, 1994.

[8] P.D. Henderson, H. Klaiman, J. Ginnetti, T. Snodgrass, N. Cohn, S. Bloor, L. VanSlyck, "Cost Aspects of AGC, Inadvertent and Time Error", IEEE Transactions on Power Systems, Vol. 5, No. 1, February 1990.

[9] L. VanSyck, N. Jaleeli, W. Robert Kelley, "Implications of Frequency Control Bias Settings on Interconnected System Operation and Inadvertent Energy Accounting", IEEE Transactions on Power Systems, Vol. 4, No.2, May 1989.

[10] W.W. Price, H. D. Chiang, H.K. Clark, D.C. Concordia, "Load Representation for Dynamic Performance Analysis", IEEE Transactions on Power Systems, Vol. 8, No. 2, May 1993.

[11] S. Banerjee, J.K. Chatterjee, S.C. Tripathy, "Application of Magnetic Energy Storage Unit as Load-Frequency Stabilizer", IEEE Transactions on Energy Conversion, Vol. 5, No. 1, March 1990.

[12] Susan M. Schoenung, Clayton Burns, "Utility Energy Storage Applications Studies", IEEE Transaction on Energy Conversion, Vol. 11, No. 3, September 1996.

[13] Z. Jiancheng, H. Lipei, Wu Su, "Research on Flywheel Energy Storage System for Power Quality" IEEE 2002.

[14] Satoshi Uemura, Shinichi Nomura, Ryuichi Shimada, "Stabilization of Electric Power System using the Variable Speed Flywheel Generator", IEEE 1997.

[15] Hans J. Bornemann, Michael Sander, "Conceptual System Design of a 5 MWh/100 MW Superconducting Flywheel Energy Storage Plant for Power Utility Applications", IEEE Transactions on Applied Superconductivity, Vol. 7, No. 2, June 1997.

[16] John D. Boyes, Nancy H. Clark, "Technologies for Energy Storage Flywheels and Super Conducting Magnetic Energy Storage", Energy Storage Program-Sandia National Laboratories, IEEE 2000.

[17] B. Bhargava, G. Dishaw, "Application of an Energy Source Power System Stabilizer on the 10 MW Battery Energy Storage System at Chino Substation", IEEE Transaction on Power Systems, Vol. 13, No. 1, February 1998.

[18] Ph.G. Rutberg, R.B. Goncharenko, E.G. Kasharsky, "About Prospects of Application of the Flywheel Stabilizer of Frequency in a Power System", Institute of Problems of Electro physics of Russian Academy of Science" IEEE 2002.

[19] GAMS/CPLEX A User's Guide, GAMS Development Corporation, 2003.

[20] Margaret Toussaint, "An Analytical Study of the Load Flow Problem", Master Thesis at McGill University, Montreal, Canada, September 1994.

[21] Ivana Kockar, "Iterative Generation of Synthetic Power System Networks for Load Flow Studies", Master Thesis at McGill University, Montreal, Canada, July 1998.