CHAPTER 5
OPTIMIZATION TECHNIQUE OF POWER TRANSFORMER

5.1 Chapter Overview

The two components of the proposed model; knowledge based model and financial model; were described and tested in the previous chapter. This chapter discusses the main component of proposed model i.e. the decision model. The flowcharts are presented to describe how the decisions are selected during the load violation of power transformers. It comprises of multiple rules to make a decision. The results are presented in the later section of this chapter with the use of four different case studies followed by the simulation software. Finally, the discussions and findings of the obtained results are provided in the last section.

5.2 Introduction

The main objective of assessing the life cycle of power transformer is to maximize the profit and minimize the cost of keeping it on the stock. The decision point is selected as the point when the power transformer will have a load violation due to deterioration of the insulation condition of the power transformer. The deterioration is faster if the transformer is operated beyond its rated capacity [IEEE Std., 1995], [S. Tenbohlen, 2001]. This thesis focuses mainly on three scenarios to make an optimal decision during load violation; use up, replacement and relocation of power transformer. The details of the life cycle decisions were explained in chapter 2.

5.3 Decision Algorithm

The decision algorithm is the step by step process to systematically assess the life cycle of the power transformer. The main part of this algorithm is the decision rules, which assist in selecting the appropriate decision on the power transformer during load violation. To ease in constructing the algorithm for the life cycle assessment of the power transformer, it is split into two parts; one for single power transformer and another for generalization (for more than one power transformers).

Acronyms have been used in this chapter and are explained as follows:

AC	Acquisition Cost
AFDL	Actual Financial Designed Life
ALD	Actual Load Demand
DLD	Designed Load Demand
EFDL	Estimated Financial Designed Life
FDL	Financial Designed life
IY_N	Installation Year of New Power Transformer
IY_E	Installation Year of Existing Power Transformer
LOE_{FR}	Lost Opportunity of Existing PT during Future Requirement
LOE_R	Lost Opportunity of Existing PT during Replacement
LV	Load Violation
MC	Mortgage Cost
NPET	Net Profit of Existing Power Transformer
NPNT	Net Profit of New Power Transformer
NSUHK	Net Savings from Utilization of Hidden Knowledge
NT	Network
PT	Power Transformer
RI	Reinstallation Year
ST	Stock
TMC	Total Mortgage Cost
TMC_C	TMC in Current Location
TMC_P	TMC in Previous Location

5.3.1 Single Power Transformer on Network

This is the case when a single power transformer is available on the network having load violation.

5.3.1.1 Flowchart

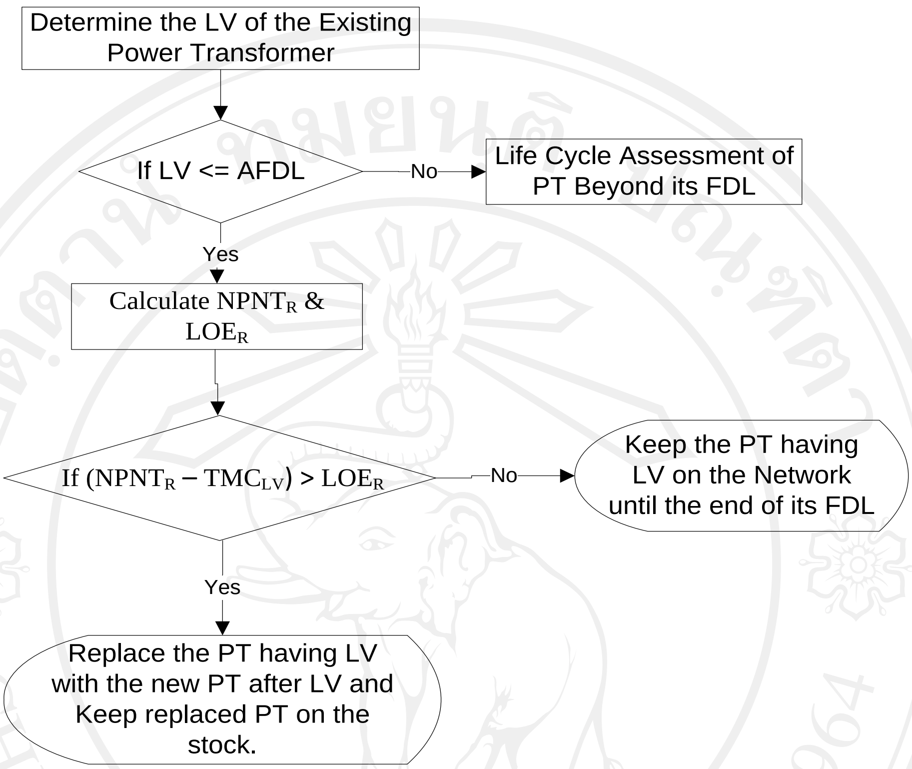


Figure 5.1 Decision Algorithm for Assessing Single Power Transformer.

5.3.1.2 Description

NPNT$_R$ is the net profit of a new power transformer during the replacement of an existing power transformer on the network after load violation. To meet the excess demand, the size of new power transformer is identified from the actual load profile of an existing one. The net profit is determined through the calculation of EVA each year starting from load violation to the end of the actual financial designed life of the existing power transformer. Mathematically, it can be represented as:

$$NPNT_R = \sum_{i=LV}^{AFDL} PV\,(EVA_i)_{ALD} + NSUHK_R \qquad (5.1)$$

The second term in the equation 5.1 represents the net savings from the utilization of hidden knowledge and is determined in a similar way to the results presented in table 4.10 in the chapter 4.

The lost opportunity of the existing power transformer is the loss of not supplying energy to the connected consumers during load violation. In other words, it is a net profit of the existing power transformer while keeping it on network after its load violation. It is represented as LOE_R. In such a situation, it cannot serve the increased load demand beyond its rated capacity. During this period, the load demand is equal to its rated capacity. LOE_R is expressed as:

$$LOE_R = \sum_{i=IY_E}^{AFDL} PV(EVA_i)_{ALD} - \sum_{i=IY_E}^{AFDL} PV(EVA_i)_{DLD}$$

(5.2)

The first term and second term in equation 5.2 show the net profit of the existing power transformer based on its actual load demand (ALD) and designed load demand (DLD) respectively.

Decision Rule: If the existing power transformer is to be replaced by the new power transformer after its load violation, the following two things can happen:

❖ The existing power transformer cannot supply energy to the connected consumers after its replacement.

❖ Each year until the end of its estimated financial designed life, the remaining mortgage cost must be paid by the existing power transformer. It is equivalent to the number of years kept on stock multiplied by its mortgage cost. Then, it can be defined as:

$$TMC_{LV} = (EFDL_E - LV + 1) * MC \quad (5.3)$$

From above, the following decision rule has been established to make a decision on power transformer during load violation:

Rule 1: If $(NPNT_R - TMC_{LV}) > LOE_R$

"Decision for Replacement"

Else

"Decision for Use Up"

5.3.2 Generalization

The decision becomes complex due to the increase in the number of power transformers. It is not straightforward because there is an affect of one power transformer to another during decision making as well as the requirement of future transformers, as illustrated in figure 5.2. With this factor in mind, the algorithm has been proposed to solve the complexity of the network problem in this context.

For instance, there are three PTs on a network to supply the load demand L. The Section of the figure on the left hand side gives the initial position of the PT before the load violation. When the load exceeds their rated capacity, better decision must be made on these three PTs and the results are presented on the right hand side of figure 5.2 along with the proposed decision algorithm. It can be noted that all three PTs (Pt1, Pt2 and Pt3) are replaced from the network after load violation by Pt2, new PT and Pt1 respectively. Finally, Pt3 is moved to stock after load violation.

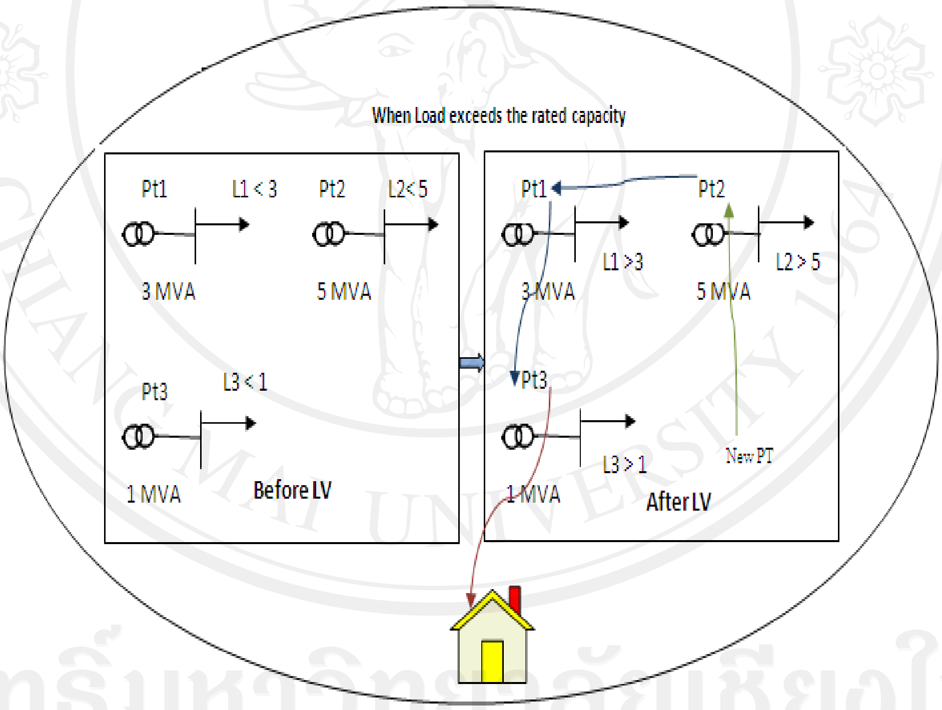
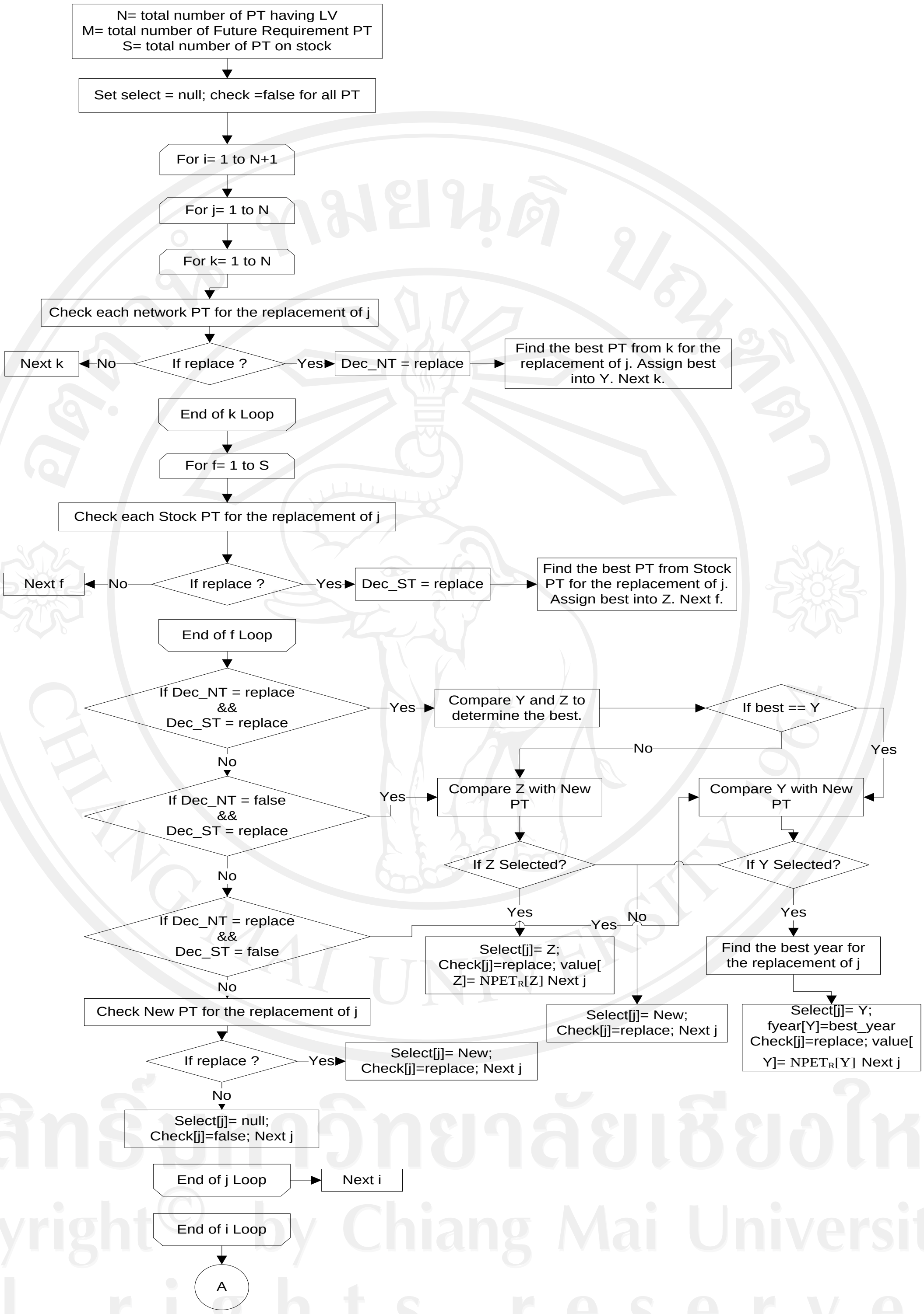


Figure 5.2 Affect on PT with the Proposed Decision Algorithm after LV.

5.3.2.1 Flowchart

The flowchart in figure 5.3 illustrates how the decisions are selected to assess the life cycle of the power transformer during load violation.



N= total number of PT having LV
M= total number of Future Requirement PT
S= total number of PT on stock
Set select = null; check =false for all PT
For i= 1 to N+1
For j= 1 to N
For k= 1 to N
Check each network PT for the replacement of j
Next k
No
If replace ?
Yes
Dec_NT = replace
Find the best PT from k for the replacement of j. Assign best into Y. Next k.
End of k Loop
For f= 1 to S
Check each Stock PT for the replacement of j
Next f
No
If replace ?
Yes
Dec_ST = replace
Find the best PT from Stock PT for the replacement of j. Assign best into Z. Next f.
End of f Loop
If Dec_NT = replace && Dec_ST = replace
Yes
Compare Y and Z to determine the best.
If best == Y
No
Yes
No
If Dec_NT = false && Dec_ST = replace
Yes
Compare Z with New PT
Compare Y with New PT
If Z Selected?
If Y Selected?
No
If Dec_NT = replace && Dec_ST = false
Yes
Yes
No
Yes
Select[j]= Z; Check[j]=replace; value[Z]= NPETR[Z] Next j
Find the best year for the replacement of j
No
Check New PT for the replacement of j
Select[j]= New; Check[j]=replace; Next j
Select[j]= Y; fyear[Y]=best_year Check[j]=replace; value[Y]= NPETR[Y] Next j
If replace ?
Yes
Select[j]= New; Check[j]=replace; Next j
No
Select[j]= null; Check[j]=false; Next j
End of j Loop
Next i
End of i Loop
A

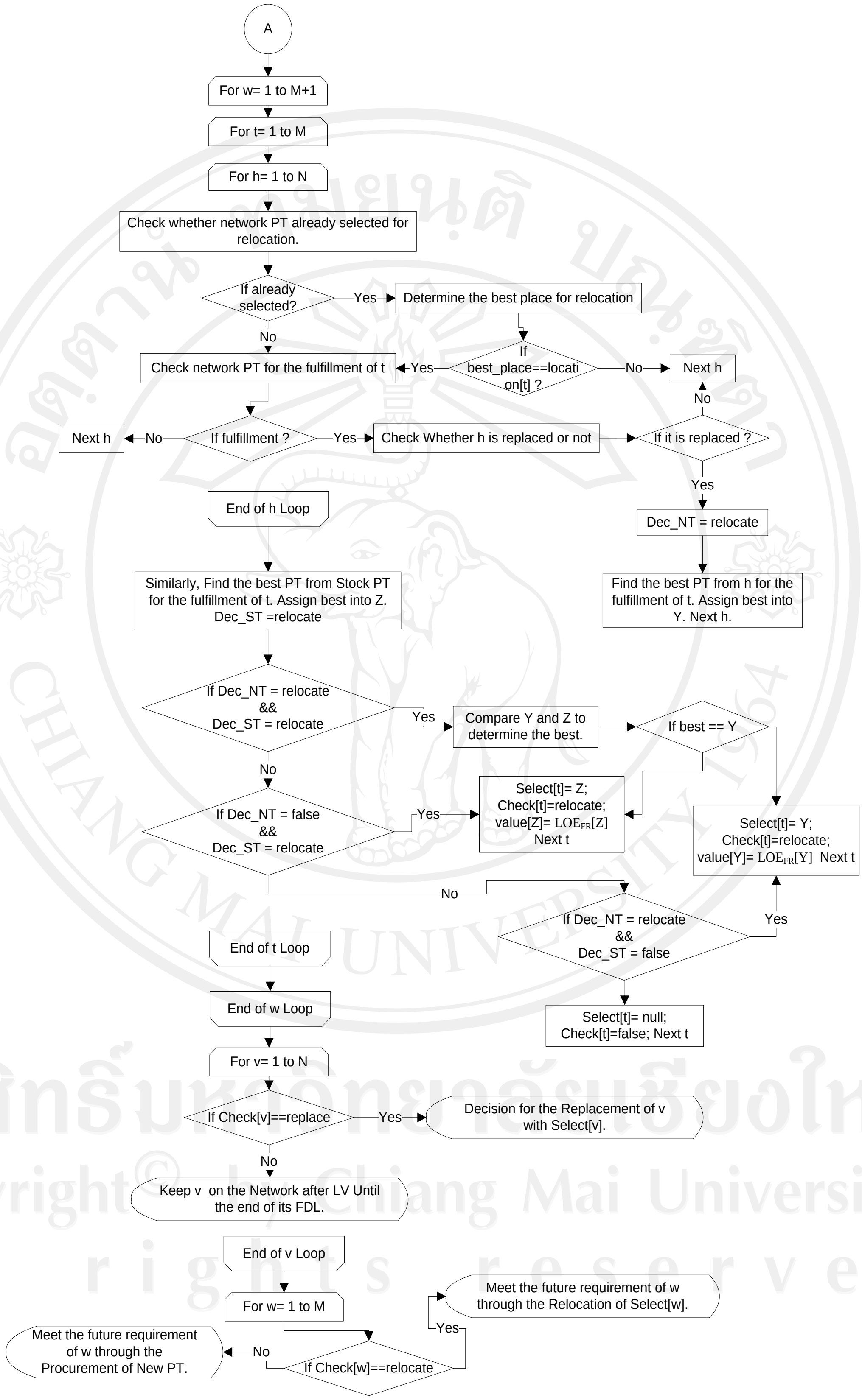


Figure 5.3 Decision Algorithm for Assessing PTs on Network.

5.3.2.2 Description

In the flowchart in figure 5.3, select and check are initialized to null and false respectively. It means that initially, all power transformers will be kept on the network after load violation and the requirement of future power transformers will be met by the procurement of new power transformers. Value is set as zero initially for all the power transformers which means that they are not selected for the relocation. DefaultLV is the actual load violation year of power transformers and LV is initially assigned to its defaultLV. On the other hand, fyear is the reinstallation year of Pt[j] and its default value is equal to its estimated end of financial designed life plus 1. The index of power transformers is represented as j, k, h and t.

1. Replacement

1.1 The following three conditions must be satisfied by the network PT for the replacement of Pt[j]:

C1.1 Capacity [k] >= ALD[j] [AFDL[j]] i.e. the capacity of PT suitable for the replacement of Pt[j] must be greater than or equal to the actual load demand of Pt[j] in year equal to AFDL.

C1.2 AFDL[k] + NS1[k] >= AFDL[j]

If LV[j] >= DefaultLV[j] {

U=DefaultLV[j] }

Else U= LV[j]

NS1[k]= U-LV[k] (5.4)

C1.3 Pt[k] must be replaced from the network.

C1.4 $NPET_R[k] - TMC_{LV}[j] >= LOE_R[j]$

The remaining mortgage cost of Pt[j] must be paid by the existing power transformer each year until the end of its estimated financial designed life.

1.2 If Pt[j] is selected for the relocation during load violation, reinstallation year is assigned into its LV and two cases will occur:

Case 1: If the reinstallation year of Pt[j] is greater than or equal to its DefaultLV, the lost opportunity of Pt[j], net profit of existing PT for the replacement of Pt[j] and remaining mortgage cost of Pt[j] can be determined with equations 5.5, 5.6 and 5.7 given below:

$$LOE_R[j] = \sum_{i=IY_E}^{AFDL} PV(EVA_i)_{ALD} - \sum_{i=IY_E}^{AFDL} PV(EVA_i)_{DLD} \quad (5.5)$$

$$NPET_R[k] = \sum_{i=U}^{AFDL} PV(EVA_i)_{ALD} + NSUHK_R - AC \quad (5.6)$$

$$TMC_{LV}[j] = MC[j] * [EFDL[j] – defaultLV[j]]-[EFDL[j] – fyear[j] \quad (5.7)$$

Case 2: If the reinstallation year of Pt[j] is less than its DefaultLV, the lost opportunity of Pt[j], net profit of existing PT for the replacement of Pt[j] and remaining mortgage cost of Pt[j] can be expressed as in equations 5.8, 5.9 and 5.10 respectively:

$$LOE_R[j] = \sum_{i=IY_E}^{AFDL} PV(EVA_i)_{ALD} - \sum_{i=IY_E}^{AFDL} PV(EVA_i)_{DLD} + \sum_{i=LV}^{DefaultLV-1} PV(EVA_i)_{ALD} \quad (5.8)$$

$$NPET_R[k] = \sum_{i=LV[j]}^{AFDL} PV(EVA_i)_{ALD} + NSUHK_R - AC \quad (5.9)$$

$$TMC_{LV}[j] = MC[j] * [EFDL[j] – RI[j]]-[EFDL[j] – fyear[j] \quad (5.10)$$

If Pt[j] is not selected for the relocation, the lost opportunity of Pt[j], net profit of existing PT for the replacement of Pt[j] and remaining mortgage cost of Pt[j] can be determined with equations 5.5, 5.6 and 5.7 respectively.

1.3 If Select[j] = k then Check[k] = replace i.e. If any PT is selected for the replacement of Pt[j], the selected Pt[k] must be replaced from the network during load violation.

1.4 If two PTs are eligible for the replacement of same PT, it is necessary to determine the best between them in the following manner given below:

Rule 2: If (TMC [A] >= TMC [B]) {

d= TMC [A] – TMC [B]

If ($NPET_R$ [A] >= $NPET_R$ [B] – d) Y=A (A is selected)

Else Y=B (B is selected)

}

Else {

d= TMC [B] – TMC [A]

If ($NPET_R$ [A] –d >= $NPET_R$ [B]) Y=A

Else Y=B

}

Where A and B are two PT, and TMC[A] and TMC[B] are the remaining mortgage cost to be paid by A and B respectively when they will be reinstalled in the location of Pt[j]. It can be expressed as below:

$$TMC\ [A] = MC\ [A] * [EFDL\ [A] - LV[j] + 1] \tag{5.11}$$

$$TMC\ [B] = MC\ [B] * [EFDL\ [B] - LV[j] + 1] \tag{5.12}$$

1.5 The following rule has been applied to compare the New PT with either the stock PT or network PT for the replacement of Pt[j]:

Rule 3: If ($NPNT_R$[j] –TMC[Y] > $NPET_R$[Y]) Select New PT for replacement of Pt[j].

Else Select Pt[Y] for the replacement of Pt[j].

1.6 If the load violation of Pt[j] is greater than the load violation of Pt[Y] then the following rules have been used to determine the best year for the replacement of Pt[j]:

Rule 4:

```
If (LV[j] > defaultLV[j]) LV[j] = defaultLV[j]
If ( LV[j] > LV[Y])  LVo=LV[Y]
Else LVo=LV[j]
AC=AFDL[Y];  k=LVo;
For c = LVo to LV[j]
    If (AC >= AFDL[j]) k=c; break;
    Else AC++
End of c loop
```

The net revenue generated by Pt[j] and Pt[Y] in the location of Pt[j] during the interval between k and LV[j] -1 are determined through equations 5.13 and 5.14.

$$EVA1\ [j] = \sum_{i=k}^{LV[j]-1} PV\,(EVA_i)_{ALD} \tag{5.13}$$

$$EVA1[Y] = \sum_{i=k}^{LV[j]-1} PV\,(EVA_i)_{ALD} \tag{5.14}$$

The total mortgage cost Pt[j] and Pt[Y] during the interval between k and LV[j] -1 is computed as follows:

$$MC1\,[j] = \sum_{i=k}^{LV[j]-1} MC[j] \tag{5.15}$$

$$MC1[Y] = \sum_{i=k}^{LV[j]-1} MC[Y] \tag{5.16}$$

Rule 5: If (LV[j] > LV[Y]) {

If (MC1[Y] > MC1 [j]) {

If (EVA1 [j] – (MC1[Y]-MC1 [j])) > EVA1[Y] {

fyear [Y]= LV[j]; LV[Y]=LV[j] ;LV[j]=LV[j]}}

Else {

fyear[Y] = k; LV[Y]=LV[Y]; LV[j]=LV[Y]}

Else {

fyear [Y]= LV[j]; LV[Y]=LV[j]}

1.7 Similarly, the same method can be applied to the stock power transformer except 1.3 condition of the network power transformer.

2. Relocation

The lost opportunity of the existing power transformer is the loss of generating revenue while not supplying energy in the location of future power transformer requirements. In other words, it is a net profit of the existing power transformer while relocating it to that location after load violation. It is represented as LOE_{FR}. $NPNT_{FR}$ is the net profit of new PT generated after keeping it on the location of the future PT requirement.

$$LOE_{FR} = \sum_{i=IY_N}^{AFDL} PV(EVA_i)_{DLD} + NSUHK_{RL} - AC \tag{5.17}$$

$$NPNT_{FR}[t] = \sum_{i=IY_N}^{EFDL} PV(EVA_i)_{DLD} + NSUHK_{RL} \tag{5.18}$$

2.1 If network PT is already selected for the relocation, it is necessary to determine the best place for relocation.

Rule 6: If (TMC_c [h] > TMC_p[h]) {

d= TMC_c[h] - TMC_p[h]

If (LOE_{FR}[h] > value[h] – d) best_place = Current_Location

Else best_place = Previous_Location

}

Else {

d= TMC_p[h] – TMC_c[h]

If (LOE_{FR}[h] - d > value[h]) best_place= Previous_Location

Else best_place = Current_Location

}

TMC_c [h] and TMC_p[h] are the total mortgage cost of Pt[h] in both current and previous locations during the interval between load violation year and reinstallation year -1.

$$TMC_c\,[h] = \sum_{i=LV}^{RIc-1} MC[h] \tag{5.19}$$

$$TMC_p\,[h] = \sum_{i=LV}^{RIp-1} MC[h] \tag{5.20}$$

Rule 7: In order to fulfill the requirement of Pt[t], the following conditions must be satisfied:

C2.1: $NPNT_{FR}$[t] –TMC[h] < LOE_{FR}[h]

TMC_{RL}[h] = MC[h]*[EFDL[h] – IY_N +1] (5.21)

Capacity[h] >= Capacity[t]

C2.2: AFDL[h] > IY_N[t]

C2.3: Check[h] = replace

2.2 The two power transformers are compared to determine the best place for relocation in the following manner:

Rule 8: If (TMC_{RL}[A] >= TMC_{RL}[B]){

d = TMC_{RL}[A] – TMC_{RL}[B]

If (LOE_{FR} [A] >= LOE_{FR} [B] – d) Y=A

Else Y=B}

Else {

$d = TMC_{RL}[B] - TMC_{RL}[A]$

If ($LOE_{FR\ R}[A] - d \geq LOE_{FR}[B]$) Y=A

Else Y=B}

2.3 Similarly, the same method can be applied to the stock power transformer except C2.3 condition of network PT.

5.4 Case Studies

Nepal electricity authority (NEA) is obliged to generate, transmit and distribute power by planning, constructing, operating and maintaining all generation, transmission and distribution facilities in Nepal's power system both interconnected and isolated. NEA currently has 36 substations situated under the control of the grid operation department of NEA having different voltage levels. They have recently about 90 power transformers in total. Each utility has their own methods for calculating the depreciation of the assets. However, NEA has adopted the straight line depreciation method [NEA, 2008]. The financial designed life of the power transformer is 20 years since the depreciation rate of distribution system assets is 5% [NEA, 2007b].

For operation and maintenance of a power transformer, the total fiscal budget is approximately 2% of its asset price per year and was determined from interviews with the senior engineers of the grid operation department of the NEA who have been working on power transformers. The soft loan interest rate is obtained from interviewing with the senior officer of national planning commission of Nepal, which is approximately 2%. The discount rate is taken as 8% in this research as it was taken 10% in 2004 [NEA, 2004] when the normal interest rate was about 10%, but has now reduced by 2% [NEA, 2008]. Through interviews with the senior supervisor of Nepal Hydro (supplier of power transformers) and senior engineers of Provincial Electricity Authority of Thailand, the costs required to hire an operation and maintenance expert and supervisor were obtained.

Operation and Maintenance expert cost Man-day = 3000USD

Supervisor cost Man-day = 1000 USD

Power factor = 0.80 [NEA, 2007b] Load factor = 52.20% [NEA, 2007a]

Warranty period = 1 year [Grid Operation Department, 2006]

Average tariff rate = 0.10 USD [NEA, 2007b]

5.4.1 Case I: Single Power Transformer

The Pt1mr is connected in a single node having capacity 1 MVA. It serves a population of about 23, 461 or 4,313 consumers during an installation year. The simple line diagram of one power transformer is shown in figure 5.4.

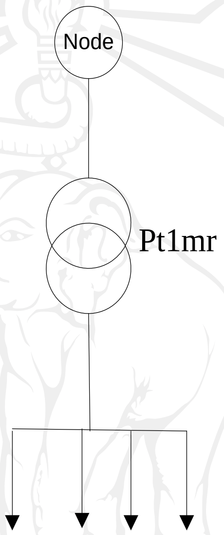


Figure 5.4 Line Diagram of Single Power Transformer.

The data of a single power transformer (Pt1mr) and new power transformer is given in table 5.1 and 5.2 respectively. Both are obtained from interviews with the senior engineers of the grid operation department, senior supervisor of Nepal Hydro (supplier of power transformers) and senior engineers of the Provincial Electricity Authority of Thailand.

Table 5.1 Data of Existing Power Transformer.

Name	Capacity	Installation Year	Asset Price
Pt1mr	1 MVA	2010	200000 $
Training Duration	**Commissioning Duration**	**Installation Duration**	**Present Status**
2 days	2 days	5 days	Network

Table 5.2 Data of New PT.

Name	Capacity	Training Duration	Commissioning Duration	Installation Duration	Asset Price
Pt_new1	3 MVA	5 days	5 days	11 days	450000 USD

The designed load is expected to grow by 15% until 2020 and then after by 2% onwards. The actual load demand is assumed to increase by 0.1 MVA. The data of the designed load demand and actual load demand is obtained from interviews with the senior engineers of the grid operation department and distribution center and is presented in table 5.3.

Table 5.3 Load Profile of Pt1mr.

Load/Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
DLD	0.2	0.23	0.26	0.3	0.35	0.4	0.46	0.53	0.61	0.7
ALD	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1
Load/Year	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
DLD	0.72	0.73	0.75	0.76	0.78	0.79	0.81	0.82	0.84	0.86
ALD	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1

5.4.1.1 Results and Analysis

The mortgage cost is calculated using equation 4.13.The load violation of Pt1mr occurs before the end of financial designed life and is obtained from the actual load demand curve in its load profile. If the transformer is not kept in the network after load violation, it cannot serve the energy during this period. Hence, the lost opportunity of this power transformer is determined using equation 5.2 and is shown in table 5.4.

Table 5.4 LOE_R and Mortgage cost of Pt1mr.

LV	Mortgage Cost (USD)	EFDL	Net profit due to ALD (USD)	Net Profit due to DLD (USD)	LOE_R (USD)
2019	12, 231.34	2029	165,808.22	30,399.58	135,408.64

If the power transformer Pt1mr is to be replaced by a new power transformer, it is in stock for 11 years. The net profit of a new power transformer is evaluated using equation 5.1 during this interval and is presented in table 5.5.

Table 5.5 Net Profit of New PT.

TMC_{LV} (USD)	$NSUHK_R$ (USD)	Net Profit of New PT	$NPNT_R$ (USD)
134,544.78	74,000.00	231,574.11	305,574.11

From the decision rule 1, table 5.6 is constructed.

Table 5.6 Decision Table during LV of Pt1mr.

($NPNT_R$ - TMC_{LV})	LOE_R	($NPNT_R$ - TMC_{LV}) > LOE_R	Decision
171,029.33	135,408.64	True	Replacement

Table 5.6 depicts that the new power transformer could provide more profit than the existing power transformer if it will be kept in the location of Pt1mr after load violation. Therefore, Pt1mr must be replaced from the existing network in 2019 with the new power transformer because it has no margin to operate in this location after load violation.

5.4.2 Case II: Three Network Power Transformers

In this case, three power transformers Pt1mr, Pt2mr and Pt3mr are installed in the network. It is illustrated by showing with line diagram in figure 5.5. Pt2mr serves about a population of 70, 382 or 12, 934 consumers during the installation year. On the other hand, a population of about 1, 87, 683 or 34,500 consumers are connected to Pt3mr in the year of installation. Pt1mr has already been described in the previous section.

The data of Pt2mr, Pt3mr and the new PT is given in tables 5.7, 5.8 and 5.9 respectively and as before, was obtained from interviews with the senior engineers of the grid operation department, the senior supervisor of Nepal Hydro (supplier of power transformers) and senior engineers of the Provincial Electricity Authority of Thailand.

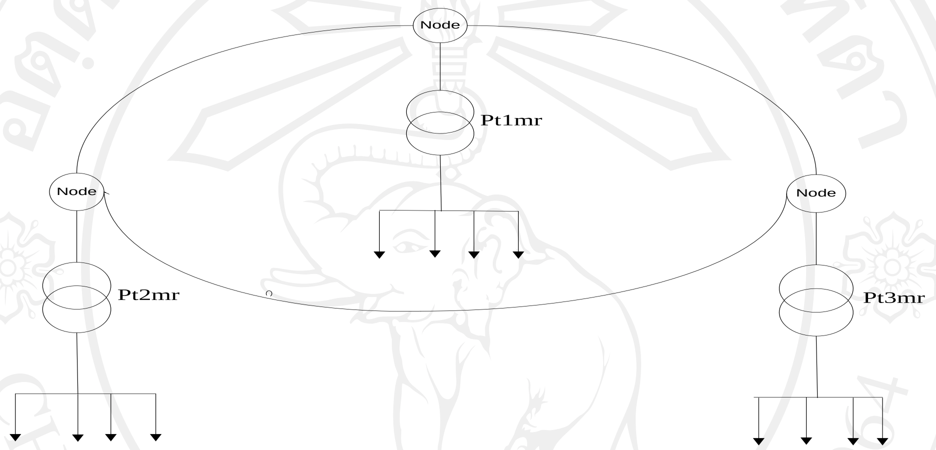


Figure 5.5 Line Diagram of the Three Power Transformers.

Table 5.7 Data of the Network Power Transformer Pt2mr.

Name	**Capacity**	**Installation Year**	**Asset Price**
Pt2mr	3 MVA	2008	450000 USD
Training Duration	**Commissioning Duration**	**Installation Duration**	**Present Status**
5 days	5 days	11 days	Network

Table 5.8 Data of the Existing Power Transformer Pt3mr.

Name	**Capacity**	**Installation Year**	**Asset Price**
Pt3mr	6 MVA	2010	600000 USD
Training Duration	**Commissioning Duration**	**Installation Duration**	**Present Status**
6 days	6 days	15 days	Network

Table 5.9 Data of the New Power Transformers.

Name	Capacity	Training Duration	Commissioning Duration	Installation Duration	Asset Price
Pt_new2	7.5 MVA	9 days	9 days	22 days	900000 USD
Pt_new3	10 MVA	10 days	10 days	25 days	1000000 USD

The actual and designed load profile of Pt2mr and Pt3mr are presented in table 5.10 and 5.11 respectively starting from installation date to the end of their financial designed life, which are again obtained from the interviews with the senior engineers of the grid operation department and distribution center. The designed load of Pt2mr is expected to grow by 10% until 2019 and then by 5% onwards whereas the designed load demand of Pt3mr is expected to increase by 10% and thereafter by 2%.

Table 5.10 Load Profile of Pt2mr.

Load/Year	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
DLD	0.6	0.66	0.73	0.80	0.88	0.97	1.06	1.17	1.29	1.41
ALD	0.6	1.1	1.6	2.1	2.6	3.1	3.3	3.5	3.7	3.9
Load/Year	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
DLD	1.49	1.56	1.64	1.72	1.81	1.90	1.99	2.09	2.19	2.30
ALD	4.1	4.3	4.5	4.7	4.9	5.1	5.3	5.5	5.7	5.9

Table 5.11 Load Profile of Pt3mr.

Load/Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
DLD	1.6	1.76	1.94	2.13	2.34	2.58	2.83	3.12	3.43	3.77
ALD	1.6	2.1	2.6	3.1	3.6	4.1	4.6	5.1	5.6	6.1
Load/Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
DLD	4.15	4.23	4.32	4.4	4.49	4.58	4.67	4.77	4.86	4.96
ALD	6.3	6.5	6.7	6.9	7.1	7.3	7.5	7.7	7.9	8.1

The load violation of Pt1mr, Pt2mr and Pt3mr are in 2019, 2013 and 2019 respectively. The proposed algorithm therefore needs to provide an optimal decision on these power transformers and the results are presented in next section.

5.4.2.1 Results and Analysis

The four conditions must be fulfilled in order to replace the existing power transformer on the network presented in section 5.3.2.2.

Two conditions are satisfied from Pt_new1, Pt2mr and Pt3mr to replace Pt1mr. The net profit of these power transformers is presented in table 5.12 along with the application of condition C1.4 due to the replacement of Pt1mr during the load violation in 2019. $NPNT_R$[Pt1mr], $NPET_R$[Pt2mr] and $NPET_R$[Pt3mr] are computed from equations 5.1, 5.6 and 5.6 respectively. TMC_{LV}[Pt1mr] and LOE_R[Pt1mr] are already determined and presented in table 5.4 and 5.5.

Table 5.12 Status of PT for the replacement of Pt1mr.

Replaced By	Net profit (USD)	Y=Net profit – TMC_{LV}[Pt1mr]	Y> LOE_R[Pt1mr]
Pt_new1	305,574.11	171,029.33	True
Pt2mr	281,569.38	147,024.60	True
Pt3mr	76,547.98	-57,996.8	False

Rule 3 is applied and presented in table 5.13 because the new and network power transformers are selected for the replacement of Pt1mr. If Pt_new1 will be used for the replacement, Pt2mr will be kept on stock after load violation of Pt1mr. TMC[Pt2mr] is the total mortgage cost of Pt2mr during that period and is determined using equation 5.11.

Table 5.13 Comparison between Pt_new1 and Pt2mr for the replacement of Pt1mr.

TMC[Pt2mr]	X=$NPNT_R$[Pt1mr] - TMC[Pt2mr]	X > $NPET_R$ [Pt2mr]	Decision
247,684.71	57,889.40	False	Replacement from Pt2mr

From table 5.13, it was found that Pt2mr is selected. Since LV[Pt1mr] is greater than LV[Pt2mr], rule 4 and 5 are applied in this case to determine the appropriate year for the replacement of Pt1mr. From this, the best year for the replacement of Pt1mr is found, which is during 2015. The final condition (C1.3) is to be checked for Pt2mr.

Similarly, Ptnew2 and Pt3mr satisfy two conditions (C1.1 and C1.2) for the replacement of Pt2mr. LOE_R[Pt2mr] and TMC_{LV}[Pt2mr] are determined from equations 5.5 and 5.7, which are 764,018.68 and 55,041.04 respectively. Table 5.14 shows the verification of the third condition (C1.4) of these power transformers. Similar to table 5.13, the same process is undertaken to construct table 5.15.

Table 5.14 Status of all Possible PT for the replacement of Pt2mr.

Replaced By	**Net profit (USD)**	**Y=Net profit – TMC_{LV}[Pt2mr]**	**Y> LOE_R[Pt2mr]**
Pt_new2	1320238.80	1265197.76	True
Pt3mr	1562067.28	1507026.24	True

Table 5.15 Comparison between Pt_new2 and Pt3mr for the replacement of Pt2mr.

TMC[Pt3mr]	**X=$NPNT_R$[Pt2mr] - TMC[Pt3mr]**	**X >$NPET_R$[Pt3mr]**	**Decision**
623798.51	696,440.29	False	Replacement from Pt3mr

Rule 5 is applied to assign the value of LV[Pt2mr] into LV[Pt3m] since LV[Pt2mr] is less than LV[Pt3mr]. Then, Pt3mr must be checked to ascertain whether it can be replaced in LV[Pt2mr] year or not. To do this, only Ptnew3 satisfies the two conditions for its replacement. The value of LOE_R[Pt3mr] is 1648671.21, and obtained from equation 5.8. If Pt3mr will be relocated at location of Pt2mr in 2013, the Pt3mr is not idle. So, the total mortgage cost TMC_{LV} [Pt3mr] to be paid by Ptnew3 for Pt3mr is zero, which is attained from equation 5.10.

Table 5.16 Status of New PT for the replacement of Pt3mr.

Replaced By	Net profit (USD)	Y=Net profit – TMC_{LV}[Pt3mr]	Y> LOE_R[Pt3mr]
Ptnew3	2077437.34	2077437.34	True

Table 5.16 is constructed to determine whether Pt3mr will be replaced by the new power transformer in 2013. It shows the positive result. A summary of results is presented in table 5.17.

Table 5.17 Optimal Decisions on the Network Power Transformers in Case II.

Power Transformers	Optimal Decisions
Pt1mr	Replacement with Pt2mr in year 2015 and Keep Pt1mr on Stock from year 2015 to end of its FDL.
Pt2mr	Replacement with Pt3mr in year 2013.
Pt3mr	Replacement with New PT in year 2013.

In conclusion, Pt2mr is replaced by Pt3mr in year 2013 and Pt1mr is replaced by Pt2mr in year 2015 because all stated conditions are satisfied. Pt2mr will be in stock for 2 years. Finally, Pt1mr is put into stock from year 2015 to the end of its financial designed life. As compared to traditional methods, it showed that the practice of buying new power transformers have been reduced, as well as a shortening of the time of keeping the power transformer on stock. In addition, the decision point has been shifted in case of Pt1mr.

5.4.3 Case III: Three Power Transformers with Two Power Transformers for Future Requirements

This case uses five power transformers in different locations to test the proposed decision model. It is similar to the case explained in section 5.4.2 except two future requirement power transformers are added to the network problem and are shown in figure 5.6. It means that there will be the requirement of power transformers in the future due to the expansion of supply to rural region. The load growth in these areas follows the designed load demand so the load profiles are same as the designed load demand of Pt1mr, Pt2mr and Pt3mr presented in tables 5.2, 5.9 and 5.10 respectively.

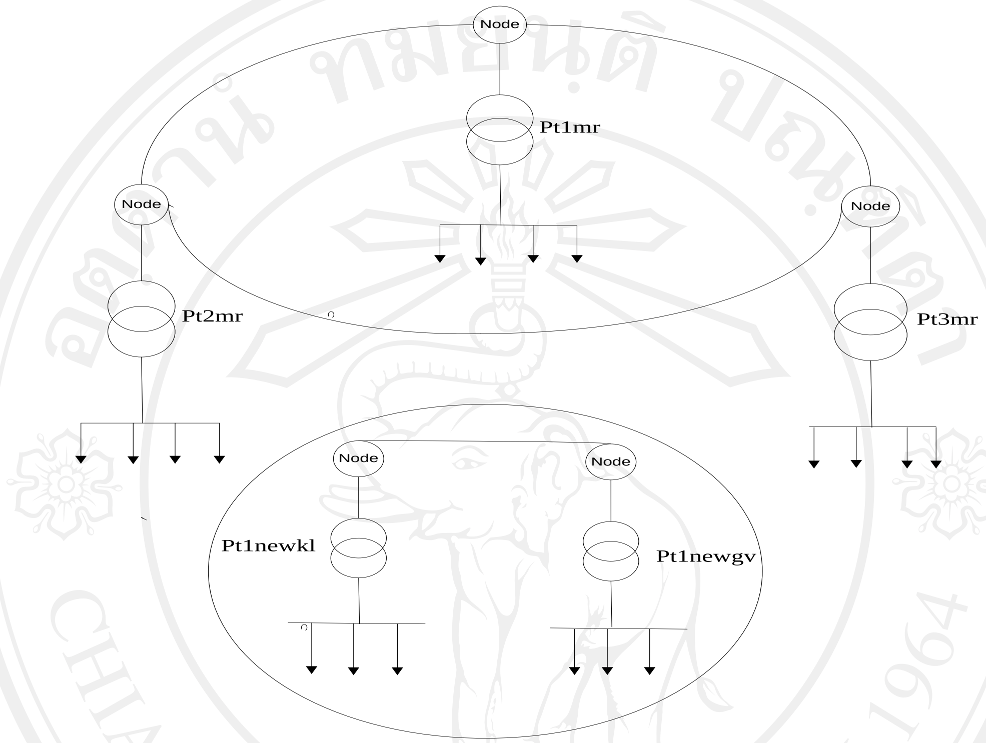


Figure 5.6 Line Diagram of both Network and Future Requirement PTs.

Table 5.18 shows the parameters of power transformers that will be required in the future and are also obtained from interviews with the senior engineers of the grid operation department.

Table 5.18 Data for future requirements of power transformers.

Name	Capacity	Installation Year	Asset Price
Pt1newkl	1 MVA	2022	225000 USD
Pt2newgv	3 MVA	2020	500000 USD

5.4.3.1 Results and Analysis

The data and parameters of the three power transformers have already been described and calculated in section 5.4.2. From results obtained in

5.4.2.1, Pt2mr and Pt3mr were selected for the replacement of Pt1mr and Pt2mr in 2015 and 2013. However, due to the addition of power transformers for future requirements, Pt2mr and Pt3mr may fulfill the requirement of Pt1newkl and Pt2newgv. In order to determine the best place to relocate Pt2mr and Pt3mr, rule 6 is applied and shown in tables 5.19 and 5.20.

Table 5.19 Comparison of location for the relocation of Pt2mr.

Relocation of Pt2mr in	**MC=Stock Keeping Cost of Pt2mr**	**N=Net Profit**	**N_C- N_A > MC_C -MC_A** (for location C)	**N_B- N_A > MC_B -MC_A** (for location B)
A=Location of Pt1mr	55041.05	281569.38	False	False
B=Location of Pt1newkl	247684.71	-95124.87		
C=Location of Pt2newgv	192643.66	178737.88		

Table 5.20 Comparison of location for the relocation of Pt3mr.

Relocation of Pt3mr in	**MC=Stock Keeping Cost of Pt3mr**	**N=Net Profit**	**N_C- N_A > MC_C -MC_A** (for location C)	**N_B- N_A > MC_B -MC_A** (for location B)
A=Location of Pt2mr	0.0	1562067.28	False	False
B=Location of Pt1newkl	110082.09	-339826.29		
C=Location of Pt2newgv	36694.03	-161419.23		

From tables 5.19 and 5.20, it can be concluded that Pt2mr and Pt3mr are relocated in the location of Pt1mr and pt2mr in 2015 and 2013 respectively. It is required to fulfill the requirement of Pt1newkl either from the procurement of a new power transformer or the relocation of Pt1mr. Using equations 5.7, 5.18 and 5.21, the values of LOE_{FR}[Pt1mr], $NPNT_{FR}$[Pt1newkl] and TMC_{RL}[Pt1mr] are calculated and presented in table 5.21 along with the application of rule 7 to select the optimal decision on Pt1newkl.

Table 5.21 Status of Pt1mr for the relocation in Pt1newkl.

Meet the requirement of Pt1newkl through	**LOE_{FR}[Pt1mr]**	**$NPNT_{FR}$[Pt1newkl]**	**TMC[Pt1mr]**	**LOE_{FR} >$NPNT_{FR}$ –TMC[Pt1mr]**
Pt1mr	3595.22	N/A	97850.75	True
New PT	N/A	50252.14	N/A	

Table 5.21 shows that the requirement of Pt1newkl is fulfilled by Pt1mr. However, a new power transformer will be procured to meet the requirement of Pt2newgv and its net profit is 123169.86. Table 5.22 summarizes the decisions taken on power transformers.

Table 5.22 Optimal Decisions on Network Power Transformers in Case III.

Power Transformers	**Optimal Decisions**
Pt1mr	Replacement with Pt2mr in year 2015.
Pt2mr	Replacement with Pt3mr in year 2013.
Pt3mr	Replacement with New PT in year 2013.
Pt1newkl	Meet the requirement through Relocation of Pt1mr.
Pt2newgv	Meet the requirement through procurement.

The results depicted that there is an affect of one power transformer to another during decision making and the process becomes more complex. With the addition of power transformers for future requirements, the Pt1mr is relocated to the location of Pt1newkl, since it still has margin to operate when compared to a new one with the utilization of hidden knowledge.

5.4.4 Case IV: Network and Future Requirement Power Transformers with One Stock Power Transformer

This case uses five power transformers in different locations to test the proposed decision model with the inclusion of one stock power transformer. It is similar to case III explained in section 5.4.3 except one stock power transformer on the network problem. It is explained in figure 5.7.

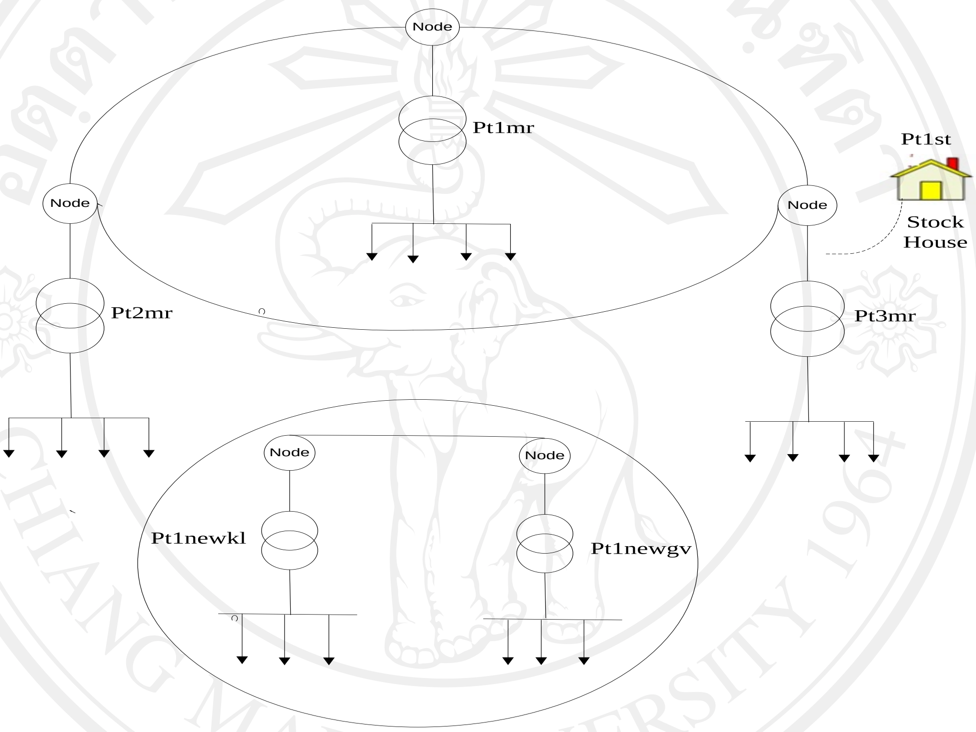


Figure 5.7 Line Diagram of Both Network and Future Requirement PTs with the inclusion of Stock PT.

The data of the stock power transformer is given in table 5.23 and the other required data of remaining power transformers are taken from section 5.4.3.

Table 5.23 Data of Stock Power Transformer.

Name	**Capacity**	**Installation Year**	**Asset Price**	**Warranty Period**
Pt1st	3 MVA	2002	450000 USD	1 year
Training Duration	**Commissioning Duration**	**Installation Duration**	**Present Status**	**Stock Keeping Year**
5 days	5 days	11 days	Stock	2008

5.4.4.1 Results and Analysis

The results obtained in section 5.4.3.1 shows that Pt2mr is already selected for the replacement of Pt1mr. Using equation 5.7, the total mortgage cost to be paid after LV due to the replacement is obtained, which is 36694.02$. Due to the presence of the stock power transformer, Pt1mr may be replaced by it since it satisfies two stated conditions for replacement.

Table 5.24 Status of Pt1st for the replacement of Pt1mr.

Replacement of Pt1mr Through	**$NPET_R$[Pt1st]**	**Y=$NPET_R$[Pt1st]-TMC_{LV}[pt1mr]**	**Y> LOE_R[Pt1mr]**
Pt1st	476275.54	341730.76	True

Table 5.24 shows that Pt1st is also eligible for the replacement of Pt1mr. Therefore, it is important to determine the best power transformers from Pt1st and Pt2mr for the replacement of Pt1mr. If Pt1st is used for replacement, Pt2mr will be kept on stock after LV of Pt1mr or vice versa. Therefore, TMC[Pt2mr] and TMC[Pt1st] are the total mortgage cost when both cannot supply energy in the location of Pt1mr after its LV and are computed using equations 5.11 and 5.12. Table 5.25 shows the application of rule 2.

Table 5.25 Status of Pt2mr for the replacement of Pt1mr.

Replacement of Pt1mr Through	**D= TMC[Pt2mr] - TMC[Pt1st]**	**$NPET_R$[Pt2mr] > $NPET_R$[Pt1st]- D**	**Condition**
Pt2mr	165123.12	281569.38>311152.42	False

From table 5.25 and the results obtained in section 5.4.3.1, it is cleared that Pt1st can replace Pt1mr in 2019 since Pt2mr does not satisfy the condition. Therefore, Pt2mr will be on stock after its load violation. The previous results showed that the requirement of Pt2newgv is fulfilled by the new power transformer in 2020. But, Pt2mr is idle during that period, there is a requirement to check whether Pt2mr can meet the needs of Pt2newgv or not using rule 7. Using equations 5.17, 5.18 and 5.21,

LOE_{FR}[Pt2mr], $NPNT_{FR}$[Pt2newgv] and TMC_{RL}[Pt2mr] are computed and presented in table.. 5.26. TMC_{RL}[Pt2mr] is the total mortgage cost of Pt2mr during that period when it will not be placed in the location of Pt2newgv. Table 5.26 depicts that Pt2mr is moved to the location of Pt2newgv for fulfilling its requirement in 2020. Finally, the results are summarized in table 5.27.

Table 5.26 Status of Pt2mr for the relocation in Pt2newgv.

LOE_{FR}[Pt2mr]	**$NPNT_{FR}$[Pt2newgv]**	**TMC_{RL}[Pt2mr]**	**LOE_{FR}[Pt2mr] > $NPNT_{FR}$[Pt2newgv] - TMC_{RL}[Pt2mr]**
178737.88	123169.87	220164.16	True

Table 5.27 Optimal Decision on Network Power Transformers in Case IV.

Power Transformers	**Optimal Decisions**
Pt1mr	Replacement with Pt1st in year 2019.
Pt2mr	Replacement with Pt3mr in year 2013.
Pt3mr	Replacement with New PT in year 2013.
Pt1newkl	Meet the requirement through Relocation of Pt1mr.
Pt2newgv	Meet the requirement through Relocation of Pt2mr
Pt1st	Move it into the Location of Pt1mr in year 2019.

The results showed that the stock power transformer can play significant role in decision making since it has changed the previous decision of Pt1mr. The decision making process becomes more and more complex with the problem of the addition of power transformers on the network. It can be found that each power transformer available on the network has been taken into consideration either for the replacement or relocation scenarios.

5.5 Simulation Software

It is seen that the decision making process becomes quite complex as shown in the cases outlined above. Keeping the complexity of the network problem in mind, automated simulation software is presented and developed to provide efficient decision making for the problem of the availability of power transformers on the network.

5.5.1 Development of Simulation Software

The development of this software process has followed the software development life cycle of the water fall model as it is easy to understand, highly visible to track and requires less customer participation [I. Sommerville, 2007]. It is completed using the following steps:

Requirement Engineering: It is important to understand what the users want to achieve from the system. In order to visualize the software system, diagrams are used. The diagram provides abstract features of the design and relationships between elements of the design. The Unified Modeling Language (UML) is widely used method for visualizing systems design. It provides various graphic tools such as use case diagrams and sequence diagrams [G. B. Shelly, 2006]. The functionality of this system is illustrated with both a use case diagram and sequence diagram. These are presented in figure 5.8 and 5.9.

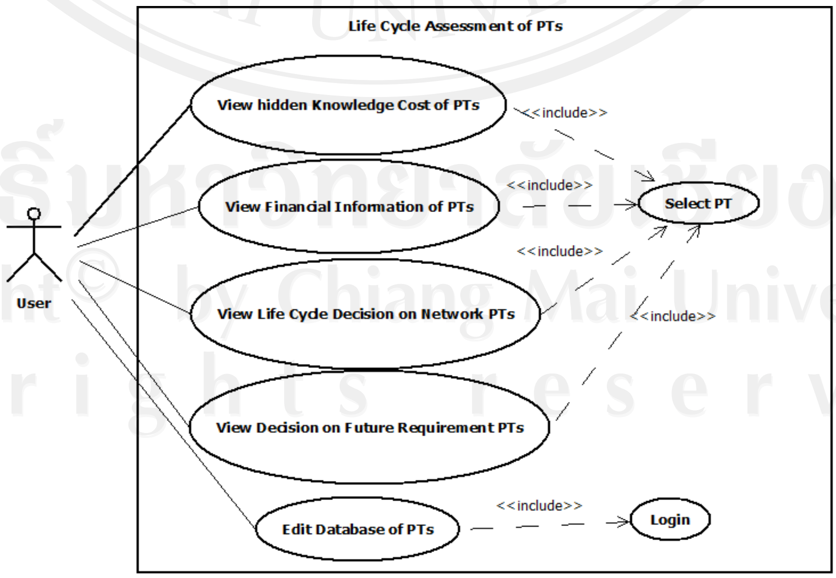


Figure 5.8 Use Case Diagram for PT Life Cycle Assessment System.

Figure 5.8 shows the functionality of this system and each use case is described with a use case description and is presented in table 5.28. It shows the interaction between user and the information system.

Table 5.28 Use Case Description.

Name of Use Case:	View Decision on Network Power Transformers
Actor:	Engineers or Executives of Power Utility
Description:	Provides life cycle decisions on selected power transformers
Successful Completion:	1. User types URL in browser: http://localhost/powertrans former/index.php/show/getFulfilling 2. Select one power transformer from the list of PTs 3. Click “Enter” button 4. System provides decision
Alternatives:	1. User types URL in browser: http://localhost/powertrans former/index.php/show/getFulfilling 2. System provides error message i.e. unable to select the specified database
Precondition:	Select at least one power transformer
Postcondition:	Life cycle assessment on power transformer has been done
Assumptions:	None

A sequence diagram of the PT life cycle assessment system is given in figure 5.9 which shows the timing of interactions between objects as they occur and all possible outcomes.

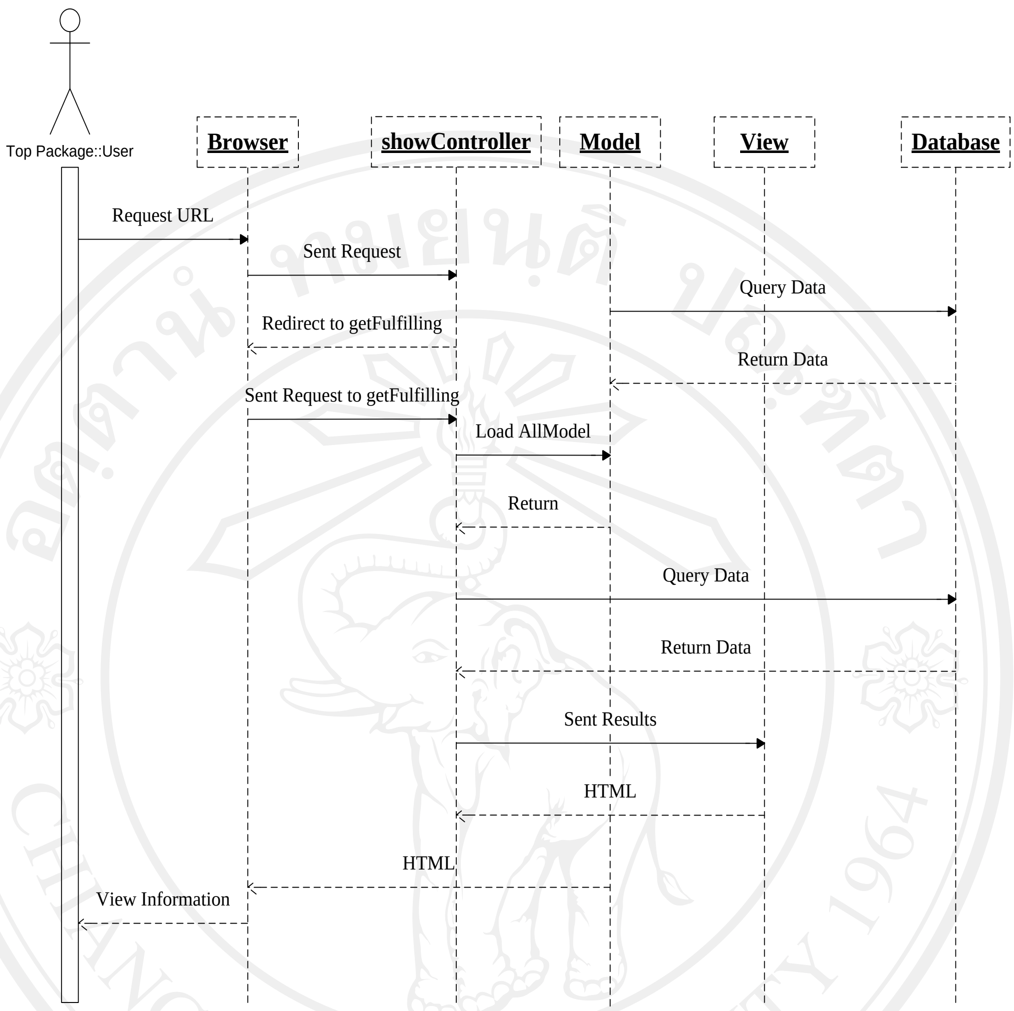


Figure 5.9 Sequence Diagram of PT Life Cycle Assessment System.

Design: It consists of interface design, architectural design and component design. The architectural design provides the structure of data and models which is shown in figure 5.11 and 5.10. In every development of a project, a major question is which technologies, programming languages, and tools are being used. In this case, the software is developed using PHP (Hypertext Preprocessor) language in the server side and MYSQL as a database. PHP was selected because of the following reasons [C. Darie, 2008]:

- It is an open source technology to build dynamic web content.
- It has a shorter learning curve than other scripting languages.
- Its community is agile. Many useful helper libraries are being developed and many new features are added frequently.

- It works well on a variety of web servers and operating systems.
- It provides support and documentation.

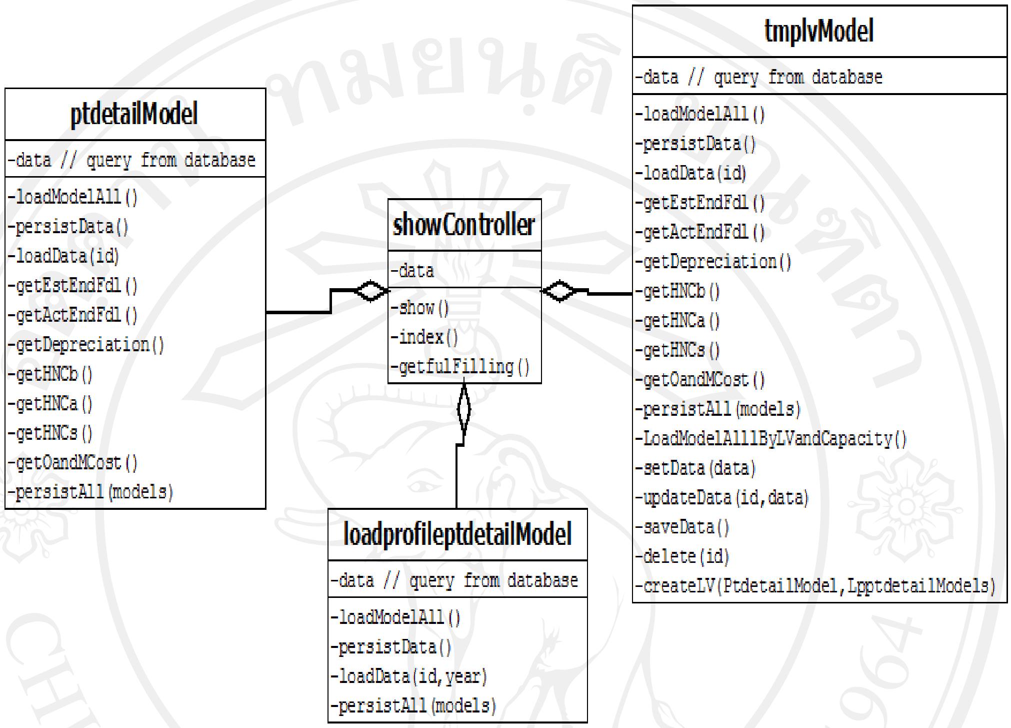


Figure 5.10 Class Diagram of PT Life Cycle Assessment System.

On the other hand, in order to store, manage, and retrieve data as quickly and reliably as possible, a relational database management system (RDMS) is required. Many RDMSs are available to use with PHP such as MySQL, PostgreSQL, Oracle, and so on. However, MySQL was selected for database since it is the world's most popular open source database, and is free, easy to use, and is a fast, and reliable database [L. Welling, 2009].

In the database of power transformers, following six main tables are constructed:

- Future requirement transformer table: Contains specific information about transformers solely for future requirements such as capacity, installation year, etc.
- Network transformers table: Contains specific information solely on network and stock transformers such as capacity, installation year, asset price, etc.

• Load profile of transformers for future requirements table: Contains designed load demand of transformers for future requirements.

• Load profile of network transformers table: Contains both designed and actual load demand of network transformers.

• New transformer table: Contains specific information solely about new transformer such as capacity, installation year, etc.

• Transformer parameters table: Contains common parameters for all power transformers such as financial designed life, soft loan interest, wheeling charge, etc.

The relationship between tables is shown in figure 5.11 using an entity relationship diagram.

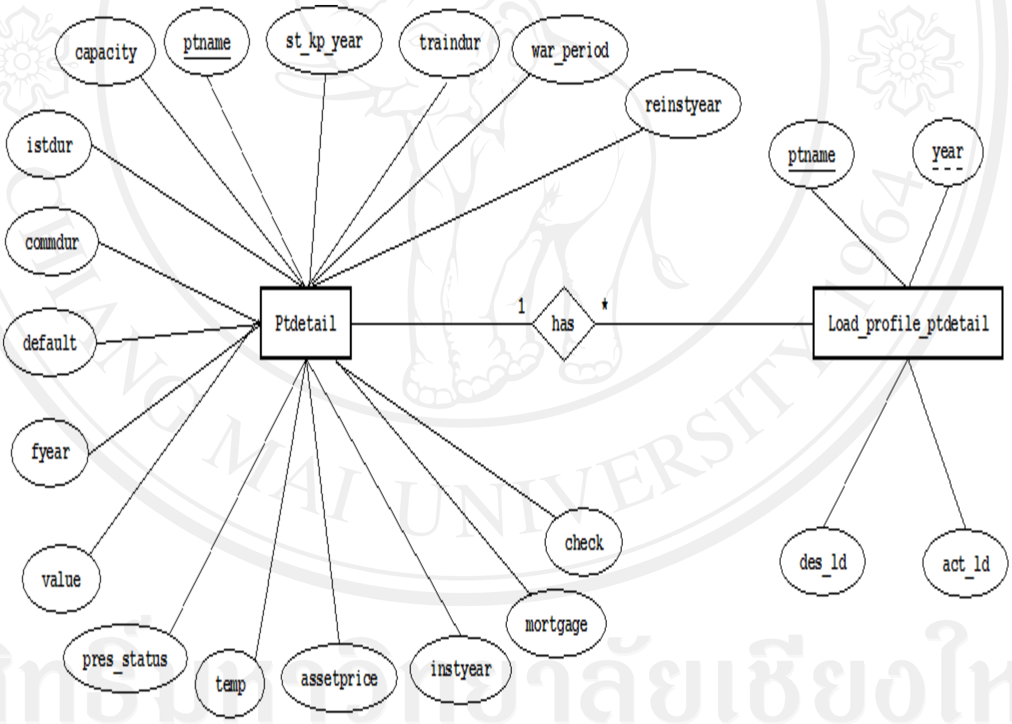


Figure 5.11 Entity-Relationship Diagram.

The component level design of this system includes user interface, framework and technologies. It is illustrated in figure 5.12. A framework is a skeleton where features can be filled or modules can be built serving as a platform. It is useful for producing consecutive applications, in which modularity and reusability of pieces of code like controllers and views are helpful. There are many frameworks that suit with

PHP such as Symfony, CakePHP, Zend, CodeIgniter, Lithium, etc. The CodeIgniter framework was chosen since it is the leading framework in 2011 due to the following reasons [B. Porebski, 2011]:

- It is lightweight and fast.
- It is easy to learn and use.
- It is flexible and adaptable.

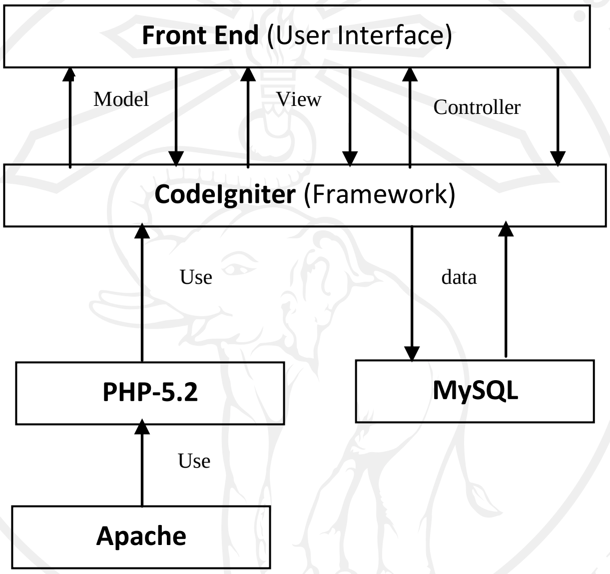


Figure 5.12 Proposed Software Architecture

The CodeIgniter framework uses a model-view-controller (MVC) design pattern to divide the application into three layers.

- Model: It represents the business logic of the application. The model has to represent the structure of data with all relationships and dependencies. It may comprise one or more classes. It uses persistent storage. It encapsulates all database connections. In addition, it also notifies the view when its internal state changes, so that the view can be refreshed.

- View: It is the output displayed to the user. It never modifies the application data.

- Controller: It is responsible for handling user interaction and taking all other actions. It should be created with simplicity in mind. It uses methods provided by the model and the view.

To successfully build web applications with web frameworks, an HTTP server is required to accept incoming connections and return output. A web browser is required to run the application on the client side. Therefore, Apache web server is used in this application as it is a widely accepted open source project [B. Porebski, 2011].

Coding: The following algorithm is used to write a code to implement the application of the power transformer. The code are written in the PHP language.

Step 1: Create a database of power transformers available in the network using MySQL. The detail of the database will be described later.

Step 2: The following parameters of power transformers are determined in the model section of the CodeIgniter framework:

- Load violation of each power transformers available on the network.
- Hidden knowledge cost before and after utilization as well as net savings from hidden knowledge.
- Actual and estimated financial designed life.

Step 3: Sort the power transformers on the network by its load violation and capacity and sort power transformers for future requirements by their installation year and capacity. Then from step 4, it is done in controller section.

Step 4: Check each power transformer for replacement either from network, stock or new power transformers.

Step 5: If the replacement is from more than one power transformers then select the best one for replacement and dec=replace and temp=best. Else go to step 6.

Step 6: Put it into the network until the end of its financial designed life. Set dec =false.

Step 7: Repeat the steps 4 to 6 until all network power transformers have been checked successfully.

Step 8: Check each power transformers' future requirement for fulfillment either from the network, stock or new power transformers through relocation or procurement.

Step 9: If the fulfillment is from the same power transformer that is already selected then select the best location for the relocation. Else go to step 11.

Step 10: If the best location is at the location of the future requirement power transformer, then dec = relocate and temp= best. The power transformer that is to be replaced by this, must be set as dec=false; temp=false; and Go to step 4.

Step 11: If the fulfillment is from more than one power transformers then select the best one for its fulfillment and Go to step 11

Step 12: If the best one is from new one, then dec = procure and temp= new. Else dec=relocate and temp=network.

Step 13: Repeat steps 8 to 11 until all future requirement power transformers have been successfully checked.

Step 14: Check from the database of each power transformers to provide decisions.

Step 15: If dec = replace then replacement of power transformer. Else use up on the network until the end of its financial designed life.

Step 16: If dec = relocate then fulfillment from relocation of power transformer.

Step 17: If dec = procure then fulfillment from relocation of power transformer.

Testing and Validation: It is tested initially with unit component and finally with the whole system. To validate the system, the results obtained from it are compared to the above results for the four different cases mentioned in earlier sections. It is shown to the engineers of the power utility for their feedback.

The database sample is given in figure 5.13 and others are included in the appendix of this thesis.

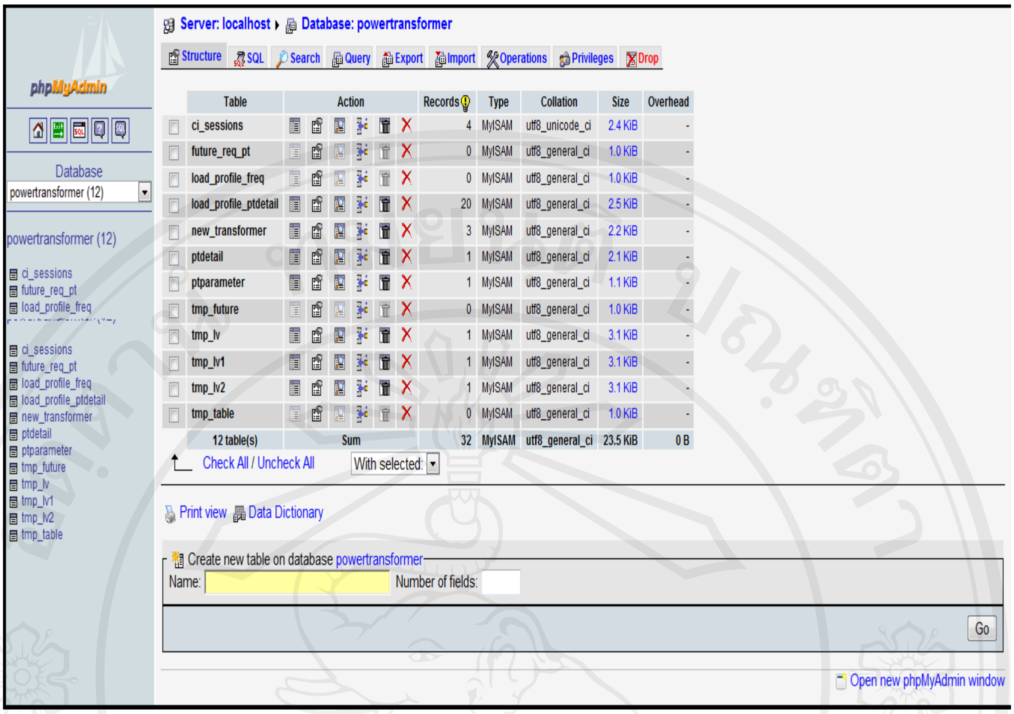


Figure 5.13 Database of Power Transformer.

Results: The application developed and presented above was implemented and provided results. Applying the previous cases within the simulation software, the results obtained are snapshots and presented in figures 5.14 to 5.17.

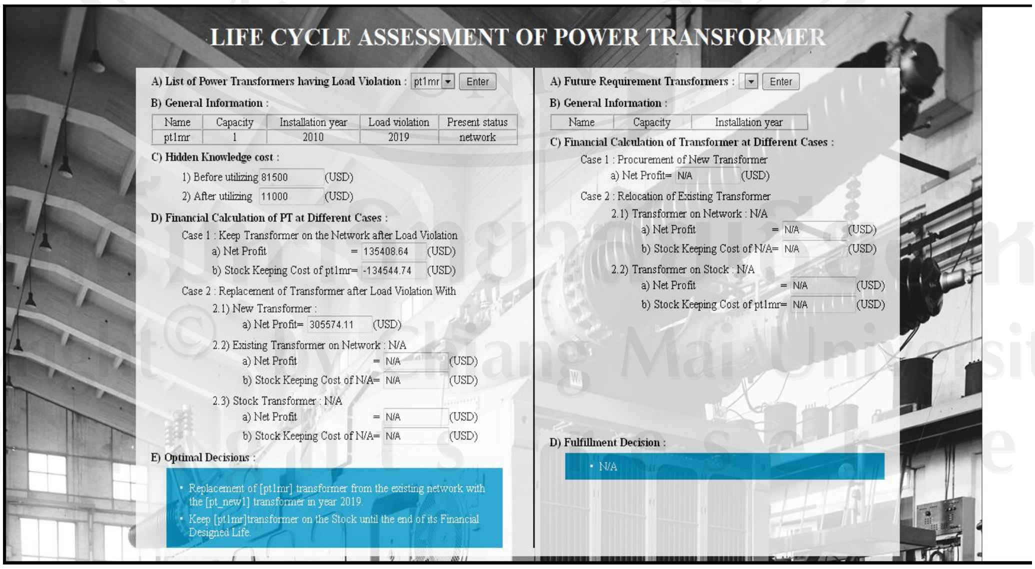


Figure 5.14 Decision on Pt1mr in Case I.

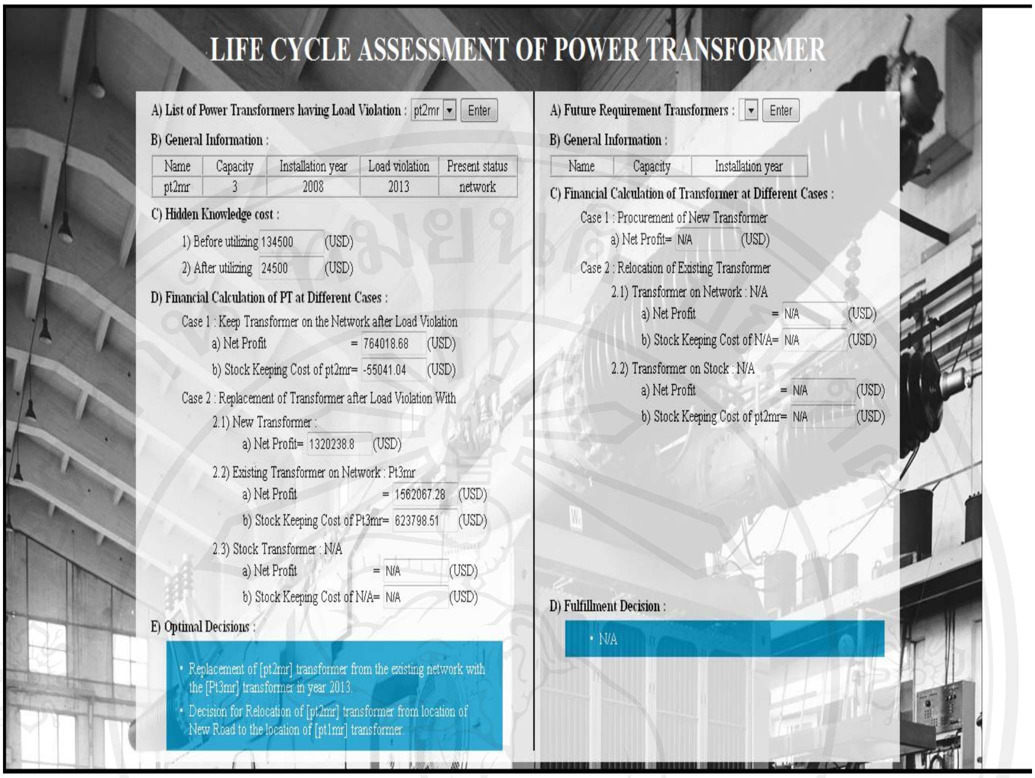


Figure 5.15 Decision on Pt2mr in case II.

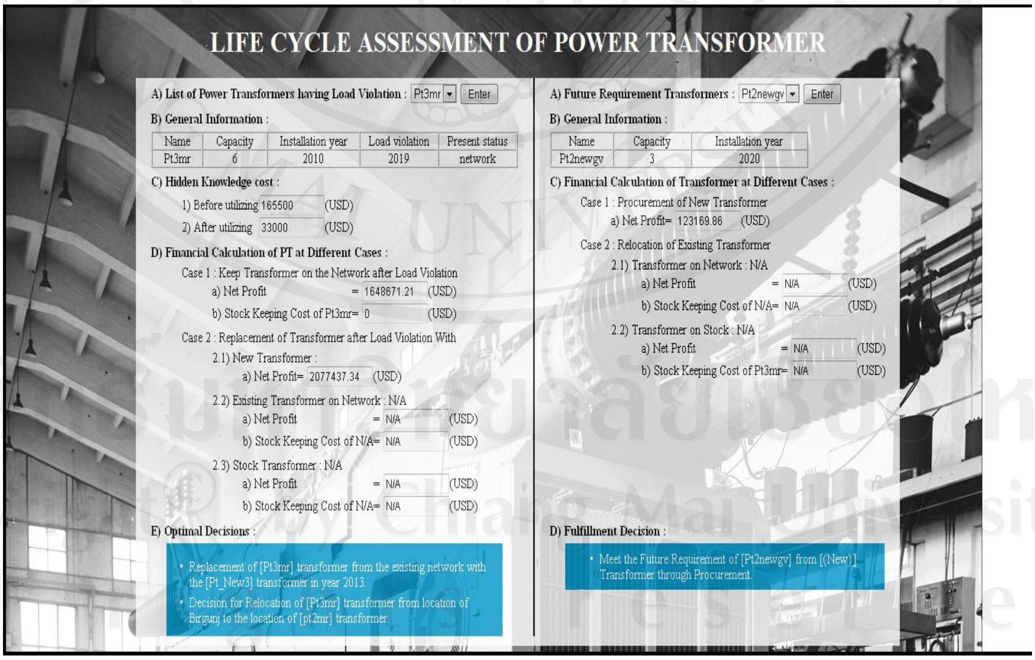


Figure 5.16 Decision on Pt3mr and Pt2newgv in Case III.

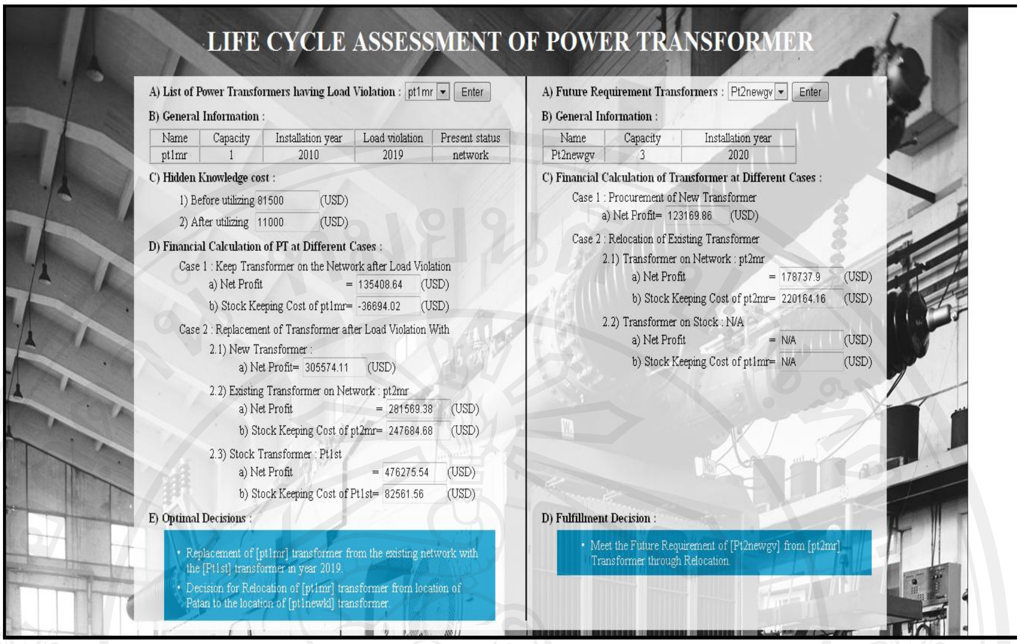


Figure 5.17 Decision on Pt1mr and Pt2newgov in Case IV.

The remaining snapshots are placed in the appendix of this thesis. From these snapshots, it can be concluded that the developed simulation software is valid and realistic for the research problem.

Limitations: Although this software can work for the problem of multiple power transformers on the network, it is difficult to validate due to increase in the number of rules and consequently validation is also difficult for decisions on the power transformer during decision making via the rule based algorithm.

5.6 Discussions

The findings and discussions of the results obtained from the above case studies can be summarized as follows:

- The results of the study show that the proposed methodology works well in assessing the life cycle of the power transformer systematically during load violation because it has considered the life of the power transformer starting from the manufacturing to the end of its financial designed life. The net profit of the power transformer is used to make optimal decision on the power transformer and is computed with the modeling of EVA inclusive of hidden knowledge.

• It is evident from the results that the decision process in a single power transformer is straightforward since it uses a single decision rule. In addition, only two options for either replacement or use up can be selected during load violation. However, with the increase in the number of power transformers, the decision process is complex and challenging because there is an affect of one power transformer on another and multiple rules are applied. In this case, three options are taken into account during decision making. Hence the decision process is iterative.

• It can be speculated that the stock management is done properly and efficiently with the minimization of transferring power transformer on stock in number as well as in a suitable timeframe. The decisions are affected by the stock keeping cost of the power transformer.

• It can be articulated that this proposed methodology can facilitate discovery of the best location for the power transformer to be relocated.

• With the use of simulation software, the power utility can assess the life cycle of the power transformer during load violation effectively and efficiently. Thus, the power utility can fully utilize the power transformer over its life cycle with the utilization of hidden knowledge under the limitation of financial resources.