The use of Markov Chain method to determine spare transformer number and location

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Article Info	ABSTRACT
	The purpose of this study is to develop a method to determine spare transformer number and location. Using Markov Chain method, state transition model and steady state probability was used on each 500-kV substation in order to analyze the effect of spare number and location variation with the reliability changes. To give an actual result of the case study, calculation of spare transformer number and location on 500/150 kV transformers in Java Bali System was analyzed. The steady state probability results will vary depending on the number of spare transformer, these results can then be used to assess the spare transformer needed. The variation of spare transformer location can be used to analyze the best possible location of the spare in order to satisfy the reliability required. The methodology presented shows an integrated calculation for determining the spare transformer number and location.

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1.   INTRODUCTION

Normal operation of a power system ensures energy flow from generation source to load demand, through its equipment. If those equipment fails, from either or both causes in random environment, the risk of blackout is increasing. A method to reduce the risk of blackout is by providing spare equipment. The effectiveness of spare equipment is determined by its ability to maintain a certain reliability value. But, maintaining a high reliability value would increase investment cost, therefore a method to determine spare transformer parameters is needed.

Spare part is important aspect in maintaining the system reliability, several methods to determine spare part has been used, some of the method already implemented in actual electrical equipment [1], [2]. A number of research have been done specifically on spare transformer number calculation, based on these literature, most of them uses Markov Chain method [3]-[8]. However, all of the research did not consider spare location. Based on an actual condition of a power system, the output should also include spare transformer location. This paper will show the advantage of the integration of spare transformer number and location calculation.

The concept of this study is reliability calculation; the reliability definition in Markov Chain Method is a steady state probability in states which is considered as a success conditions. To obtain the above results, the calculation of reliability is calculated for each 500-kV substation by varying the amount and location of the spare transformer. In order to give clear implementation of the method, this research uses 500/150 kV transformer in Java-Bali System as the case study.

2.   RESEARCH METHOD

The main framework used in this research is Markov Chain Method. Based on the Markov Chain Model [9], [10], the definition of system reliability is the steady probability group of normal condition states (success states). The first step in Markov Chain Model is by making a state transition model. This research will use one spare transition state model, as shown on the Figure 1.
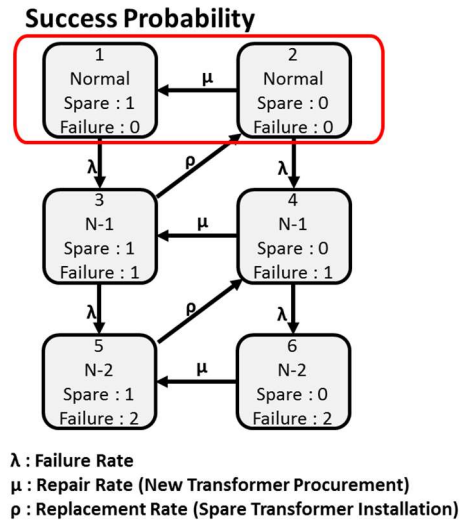

Figure 1. Transition state model of one spare transformer

Based on the Figure 1 and referring to the actual condition, the probability group of system reliability will be the steady state probability in state 1 and state 2. while other states are defining an abnormal operation, the definition of each states are:

a. State 1 is normal condition with 1 spare available and without any system failure.
b. State 2 is normal condition with no spare available and without any system failure.
c. State 3 is N-1 condition with 1 spare available and with system failure.
d. State 4 is N-1 condition with no spare available and with system failure.
e. State 5 is N-2 condition with 1 spare available and with 2 transformer disturbance (system failure).
f. State 6 is N-2 condition with no spare available and with 2 transformer disturbance (system failure).

Based on the Figure 1, there are three rates that will affect the calculation result which are failure rate (λ), procurement rate (μ), and transport rate (ρ). The failure rate (λ) value is derived from A-B-C classification concept. The procurement rate (μ) is a constant value where there are no constrain in spare procurement. The transport rate (ρ) is derived with spare location variation value.

The failure rate calculation uses A-B-C Classification (Pareto Law Concept) [11]. All of the assets must be classified into 'models'. The disturbance data which affected the failure rate are only those disturbances occurred on the A component based on the A-B-C classifications. For asset classification, the method used is inventory management. Inventory Management is an activity of monitoring and controlling the business and production processes of a company, from the beginning of the booking, storage, using the components, until the production process. This method has been used to classify different 'models' of any assets. The reason why these classification is necessary is because in this research, each 'model' defines the reliability in every 500-kV substations. Each 'model' has its own failure rate, therefore to calculate this failure rate, the disturbance data needs to be classified by using Pareto Law. The Pareto principle, also known as the 80/20 rule, is a theory which says that 80 percent of the output from any given situation or system is determined by 20 percent of the input.

The next step is determining the μ value and ρ value. Based on an ideal repair and preventive maintenance [12], [13] concept, these values have uniform probability density based on the following formula,

$$f_R = 1/T_M(e^{\frac{T_M}{4}-1})\tag{1}$$

The difference is, the μ value will be constant for every variation but the ρ value will have variation value based on the spare transformer location. The one spare transition state has six possibilities of states; therefore, the calculation of the transition matrix is as shown in Figure 2.

TRANSITION MATRIX							
		TO					
		1	2	3	4	5	6
FROM	1	1-λ	0	λ	0	0	0
	2	μ	1-μ-λ	0	λ	0	0
	3	0	ρ	1-ρ-λ	0	λ	0
	4	0	0	μ	1-μ-λ	0	λ
	5	0	0	0	ρ	1-ρ	0
	6	0	0	0	0	μ	1-μ

Figure 2. One Spare Matrix Transition

By definition, this research calculates the steady state probability. Mathematically, steady state probability is a condition where any initial state when multiplied with the transition matrix will have the same output as the initial state.

$$[\text{Intial State}] \times [\text{Transition Matrix}] = [\text{Initial State}] \tag{2}$$

Calculating the above formula by using the principle of matrix calculation will give the steady state probability results. The required output is the probability group values of all states which has normal conditions. Based on the above simple example, the output is the sum of steady state probability of state 1 and state 2.

3.   METHODOLOGIES

This paper will determine the spare transformer number and location by reliability of each 500-kV substation. The main framework used is Markov Chain Model therefore the reliability is the steady state probability of Markov Chain Calculations.

3.1. General description of the proposed model

In order to have comprehensive effect, every 500-kV substation have its state transition model, therefore it have its own failure rate based on the disturbance data of each substation and different transportation rate based on the location variation.

3.2. Location variation

The idea of transportation rate variation is based on the different range between 500-kV substation. This assumption regarding the spare transformer, is located in the 500-kV substation, not in a special spare warehouse. The visualization of location variation based on Table 1.

Table 1. Substation Range Table

		To		
		A	B	C
	A	0	2	6
From	B	2	0	3
	C	6	3	0

In order to utilize the reliability value of each 500-kV substation, every substation has its own Markov Chain model and its own calculation results, while every model is linked to each other by the installation rate (ρ). Based on this definition, the location determination is the effect of component reliability when the installation rate (ρ) changes. This installation rate value changes based on the distance changes between substations. The mathematical formula of the ideal rate [12], [13] is,

$$f_R = 1/T_M(e^{\frac{T_M}{4}-1}) \tag{3}$$

Therefore, the distance calculated from Table 1 will be converted into period (TM) by rough assumption of a distance per time constant factor. These assumptions were based on several actual spare transformer transportations between the substations. The installation rate will be different for every component's reliability even though each substation will have the same Markov Chain model but different installation rate and different failure rate.

3.3. Value of lost load

The Markov Chain calculation will produce the probability steady state of success states or reliability. Based on the results, the economical calculation should give exact number and location based on the cost/benefit analysis of spare provision. The cost component is spare price or cost, but the benefit instead of production cost or tariff, this research uses value of lost load. The first step of coming up with the benefit component is calculating the outage cost,

$$\text{Outage Cost} = (1-\text{reliability}) \times \text{capacity} \times LF \times VoLL \times time \qquad (4)$$

And the Value of Lost Load calculation is:

$$VoLL = \frac{Regional\ GDP}{Energy\ Consumption} \times \frac{Business+Industry}{Total\ Consumers} \qquad (5)$$

VoLL calculation assume that any electricity outages will affect the economic condition [14].

4. RESULTS & DISCUSSION

500/150 kV transformer of Java Bali System was used as case study. These transformers had several conditions that needed to be classified in order to have logical calculations of spare amount number and location:
1. Classification
   a. 1 phase per banks or 3 phase per bank.
   b. 2 kinds of impedance.
   c. Locations throughout Java
2. Failure rate calculation

Inventory management was used to classify the above conditions into several "models". These models had their own failure rates, which would be derived from Pareto Law–ABC Classifications. The next step was steady state probability calculation for every failure rates and each variation of spare location.

4.1. Java Bali 500/150 kV transformer model

500/150 kV Transformer or Inter Bus Transformer (IBT) in Java Bali System has two types, which are the single phase per bank transformer and the 3 phase per bank transformer. The majority of the IBT in Java Bali system are single phase per banks transformer. The advantages of single phase per banks transformers are the flexibility of the spare transformer, where if there is a failure in one of the transformer, the spare will replace only one unit instead of all three. Moreover, it is lighter than 3 phase per bank transformer, where the advantage will be on transportation method aspect. The type of the transformer used for this calculation is shown in the transformer type graphical recap in Figure 3.

Looking at Figure 3, the single phase per bank transformer has two type of impedance. For this study the impedance difference will be neglected. The effect will be the loading differences, therefore in order to have good results of spare number and location, the loading differences when there is different impedance will be neglected.

The next logical way to classify the IBT was dividing substation location in Java-Bali System by its provinces. This logic is based on the transportation constrain in order to have spare location and economical calculations. There are 7 provinces in Java Bali System but only 5 provinces have the 500 kV Substation. The IBT data by provinces is shown in Figure 4.
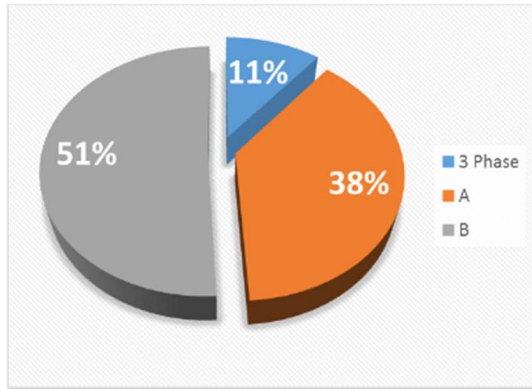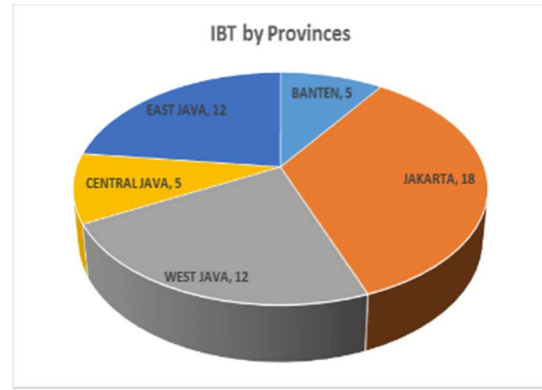
Figure 3. 500/150 kV Transformer Type

Figure 4. 500/150 kV Transformer by Provinces

Next step is determining the transformer failure classification, in order to have failure rate of each 'models'. Classification of disturbances type was recorded and compiled by maintenance engineer on Extra High Voltage Substation. The data type of this failure was taken from disturbance data from 2008 up to 2013. In order to get the failure rate, the disturbance data needs to be defined into major disturbance and minor disturbance. Pareto Law-ABC classification [11] has become a commonly used method, where the classification of A only has 20% volume of the total equipment but have the interference effect of 80%. In a transformer, this principle means, the small component of a whole equipment, could disturb the whole transformer.

Based on A-B-C classification method, the transformer failure data was divided into failure/disturbance on component A, component B, and component C of the whole transformer. A-B-C classification analysis simplified the component disturbance data based on the Pareto Law where the definition of component A in this study is a component where its disturbance has major effect on the entire transformer and this component is unique. Component B is defined as components that has a high investment value but does not affect the entire transformer in maintenance or replacements phase. Component C is defined as supporting components. Based on the definition of the classification of A-B-C above, it can be summarized that:
1. Disturbance of component A were Bushing & Insulators, and OLTC, by 19 %.
2. Interference Protection System of Component B by 31 %.
3. Impaired Support Tools of Component C which, Outer Party, and system conditions, by 49 %.

Due to data limitations and monitoring equipment, Figure 5 is showing the different classification types of disturbance per IBT 500/150 kV components in Java-Bali system for major disturbance. According to Pareto Law–A-B-C Classification, the Component A failure will have major effect to the entire transformer and also to the entire power system. Based on the classification of location and impedance, the failure rate from the disturbance data has been simplified into its average number. The failure rate calculation was using three units of transformer as one. This condition occurred because Java Bali System uses 1 phase per bank transformer, therefore one disturbance in one unit will fail all of the three units.
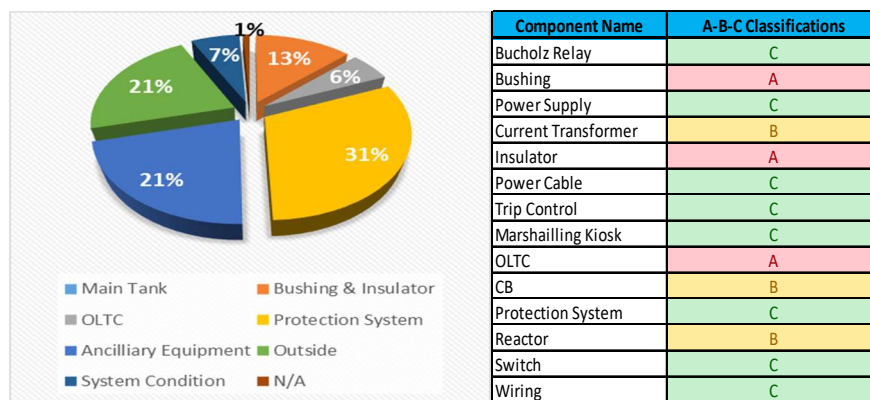

Component Name	A-B-C Classifications
Bucholz Relay	C
Bushing	A
Power Supply	C
Current Transformer	B
Insulator	A
Power Cable	C
Trip Control	C
Marshailling Kiosk	C
OLTC	A
CB	B
Protection System	C
Reactor	B
Switch	C
Wiring	C

Figure 5. Component Disturbance & A-B-C Classifications

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4.2. Failure rate

Based on Section III, the first step is detailing the failure rate(λ) into every 500-kV substation. The results are shown in Figure 6 The results of the above figures were using statistical data for every IBT in Java Bali System. The calculation of failure rates of each substation was based on A-B-C classification.
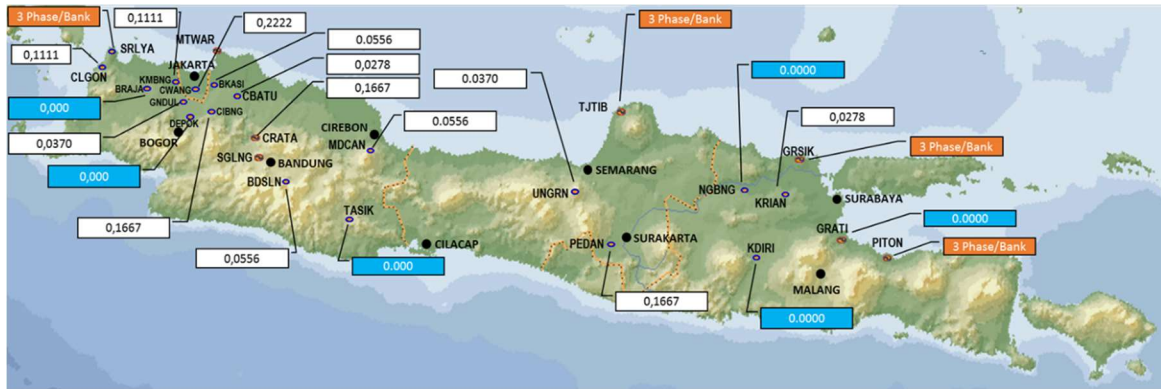

Figure 6. 500 kV Substation failure rate

4.3. Transportation rate

The next step is modeling the range data between 500 kV substations, the transportation model is shown in the Table 2 Based on the above data assumption, there will be a significant installation rate value. The one-spare Markov Chain model on each substation is linked to each other by the installation rate value.

Table 2. Range Between Each 500-kV Substation

	TO TASIKMALAYA	TO CIRATA	TO CIBATU	TO UNGARAN	TO PEDAN	TO GRATI	TO PAITON	TO KEDIRI	TO NGIMBANG	TO KRIAN	TO GRESIK	TO SURALAYA	TO SURALAYA BARU	TO CILEGON BARU	TO CIBINONG	TO KEMBANGAN	TO GANDUL	TO BEKASI	TO CAWANG	TO DEPOK	TO BANDUNG SELATAN	TO MANDIRANCAN
FROM SURALAYA	300	170	135	500	550	800	855	700	700	745	745	0	0	10	115	80	95	105	100	100	220	290
FROM SURALAYA BARU	300	170	135	500	550	800	855	700	700	745	745	0	0	10	115	80	95	105	100	100	220	290
FROM CILEGON BARU	285	165	135	500	555	765	855	700	700	745	745	10	10	0	110	80	95	105	100	100	205	290
FROM CIBINONG	175	55	30	390	440	690	750	585	585	635	635	105	105	110	0	35	20	30	20	15	100	180
FROM KEMBANGAN	210	90	55	420	470	715	775	615	620	665	675	80	80	80	35	0	20	25	20	25	135	200
FROM GANDUL	195	75	40	410	460	705	765	600	605	655	655	95	95	95	20	20	0	30	10	10	120	195
FROM BEKASI	185	65	30	400	445	685	745	585	585	635	645	100	100	100	30	25	30	0	15	30	115	180
FROM CAWANG	190	70	35	405	455	700	755	600	600	645	650	100	100	100	20	20	10	15	0	20	120	190
FROM DEPOK	190	70	40	405	455	700	765	600	605	650	655	100	100	100	15	25	10	30	20	0	115	190
FROM BANDUNG SELATAN	80	50	90	315	355	605	670	500	510	560	565	220	220	205	100	135	120	115	120	115	0	105
FROM MANDIRANCAN	70	125	155	215	265	510	570	410	415	460	460	290	290	290	180	200	195	180	190	190	105	0
FROM TASIKMALAYA	0	120	160	245	275	535	595	425	440	485	490	300	300	285	175	210	195	185	190	190	80	70
FROM CIRATA	120	0	40	345	390	640	700	535	540	585	590	170	170	165	55	90	75	65	70	70	50	125
FROM CIBATU	160	40	0	370	420	665	725	565	565	610	615	135	135	135	30	55	40	30	35	40	90	155
FROM UNGARAN	245	345	370	0	65	295	355	195	195	245	250	500	500	500	390	420	410	400	405	405	315	215
FROM PEDAN	275	390	420	65	0	255	320	150	170	215	225	550	550	555	440	470	460	445	455	455	355	265
FROM GRATI	535	640	665	295	255	0	60	115	100	60	65	800	800	765	690	715	705	685	700	700	605	510
FROM PAITON	595	700	725	355	320	60	0	170	160	115	120	855	855	855	750	775	765	745	755	765	670	570
FROM KEDIRI	425	535	565	195	150	115	170	0	65	85	105	700	700	700	585	615	600	585	600	600	500	410
FROM NGIMBANG	440	540	565	195	170	100	160	65	0	45	55	700	700	700	585	620	600	585	600	605	510	415
FROM KRIAN	485	585	610	245	215	60	115	85	45	0	20	745	745	745	635	665	655	635	645	650	560	460
FROM GRESIK	490	590	615	250	225	65	120	105	55	20	0	745	745	745	635	675	655	645	650	655	565	460

4.4. Spare number and location results

The steps are putting the spare transformer at Cilegon Substation, by using the data in Table 2. The installation rate on Markov Chain model at Cilegon Substation, and another different substation. Thus, the steady state probability group at each Substation will be different. The second scenario and so on is done by changing the spare transformer location. The location optimization is the steady state probability group calculation result that changes as the installation rate changes as well. The results calculation of probability steady state of each 500-kV substation with spare IBT location variation is shown in Table 3.

Based on the results above, each provinces should have a spare, because the significant increase of reliability occur from 0 spare to 1 spare. Based on the reliability calculation, the spare number should be 5 (1 in every province) and the optimum locations are Cilegon, Gandul, Cibatu, Ungaran, and Krian (Green color). The next calculation is by comparing these with the economic criteria.

Table 3. Calculation Results

GITET	0 Spare	1 Spare	2 Spare	3 Spare	4 Spare
Suralaya	-	-	-	-	-
Suralaya Baru	-	-	-	-	-
Cilegon	0.4718932	0.9493701	0.9620499	0.9633226	0.9634550
Balaraja	-	-	-	-	-
Kembangan	0.7015161	0.9706113	0.9776816	0.9776816	0.9776816
Cawang	0.2235391	0.8532107	0.8532107	0.8532107	0.8532107
Gandul	0.7962396	0.9860126	0.9860126	0.9860126	0.9860126
Depok	-	-	-	-	-
Bekasi	0.7015161	0.9670808	0.9688456	0.9776816	0.9776816
Cibinong	0.3203320	0.8883486	0.8883486	0.8883486	0.9107184
Cibatu	0.8461596	0.9898468	0.9898468	0.9898468	0.9898468
Cirata	0.3203320	0.8663371	0.8663371	0.8663371	0.9107184
Bandung Selatan	0.7015161	0.9459764	0.9776816	0.9776816	0.9776816
Mandirancan	0.7015161	0.9233003	0.9407244	0.9776816	0.9776816
Tasikmalaya	-	-	-	-	-
Pedan	0.3203320	0.8393674	0.9107184	0.9107184	0.9405737
Ungaran	0.7962396	0.9860126	0.9860126	0.9877685	0.9877685
Tanjung Jati	-	-	-	-	-
Kediri	-	-	-	-	-
Ngimbang	-	-	-	-	-
Krian	0.8461596	0.9899606	0.9908443	0.9908670	0.9908676
Grati	-	-	-	-	-
Gresik	-	-	-	-	-
Paiton	-	-	-	-	-

4.5. Spare number and location by economical criteria

The economic criteria are comparing the cost and benefit. The cost component is spare transformer price, with the assumption of Rp 3.24 B (around 240.000,- USD) The benefit component is the outage cost with value of lost load, whereas the value of lost load in each province is shown in Table 4. Based on the above calculation results and the calculation result of spare cost, the outage cost with spare number and location variation are calculated and analyzed. The results for 500-kV Substation in Banten in Figure 7.

Table 4. Value of Lost Load

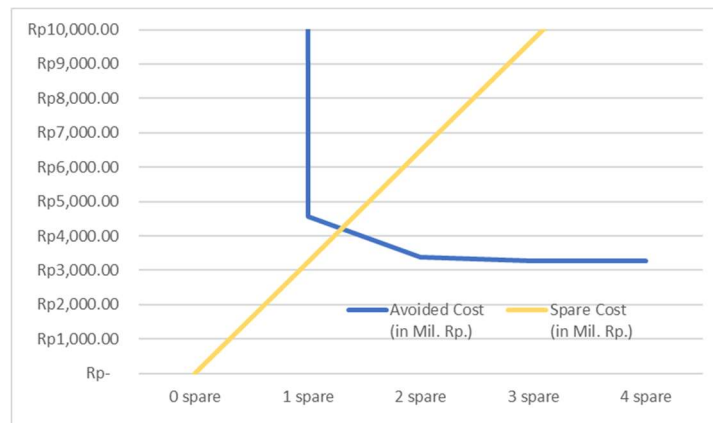| Provinces	Value of Lost Load	
Banten	Rp 4,247	/kwh
Jakarta	Rp 8,888	/kwh
West Java	Rp 4,906	/kwh
Central Java	Rp 4, 481	/kwh
East Java	Rp 7, 300	/kwh

Figure 7. Cilegon 500-kV substation results

Based on the above results, the spare number is 1 referring to the crosspath between spare cost and avoided cost, and spare location in Cilegon Substation (no other 500 kV substation). The next results for 500-kV Substation in DKI Jakarta in Figures 8-12.
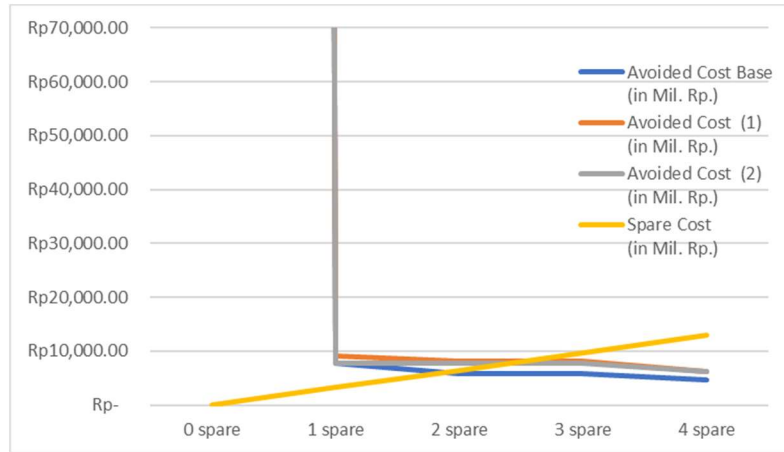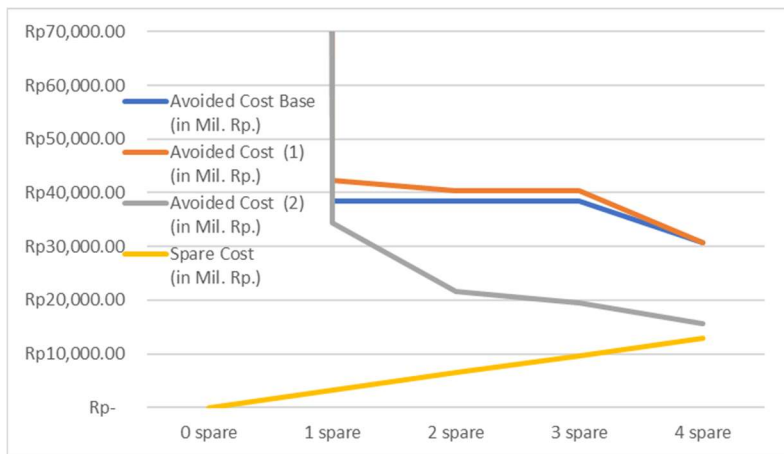
Figure 8. Kembangan 500-kV substation results

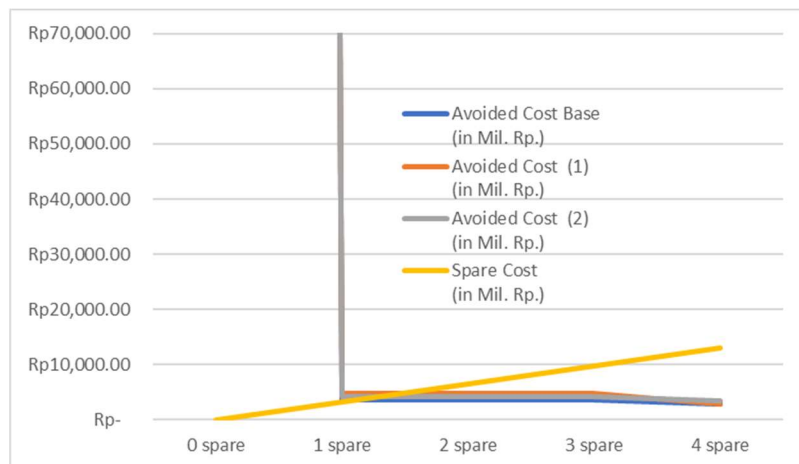Figure 9. Cawang 500-kV substation results

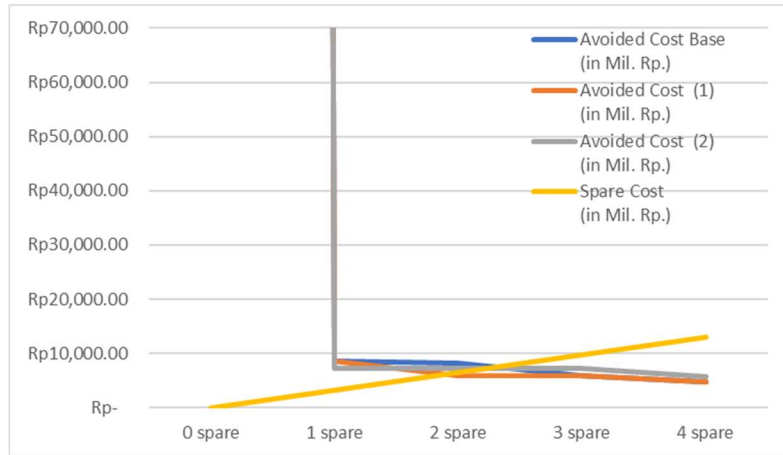Figure 10. Gandul 500-kV substation results

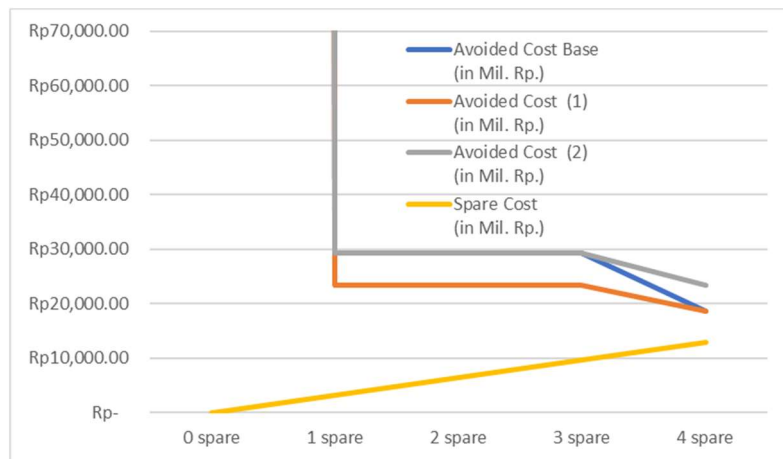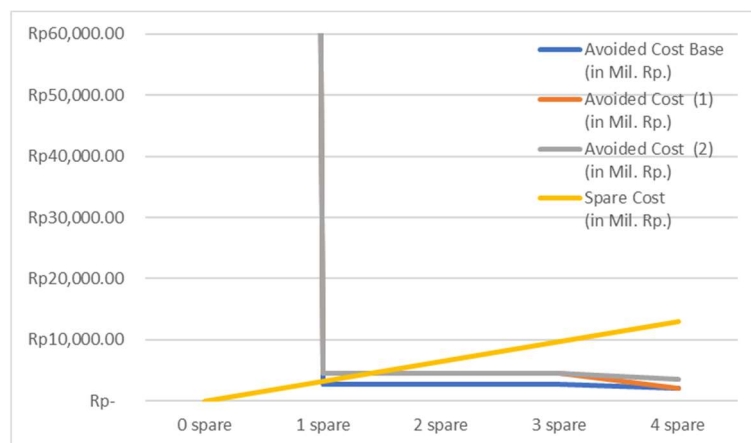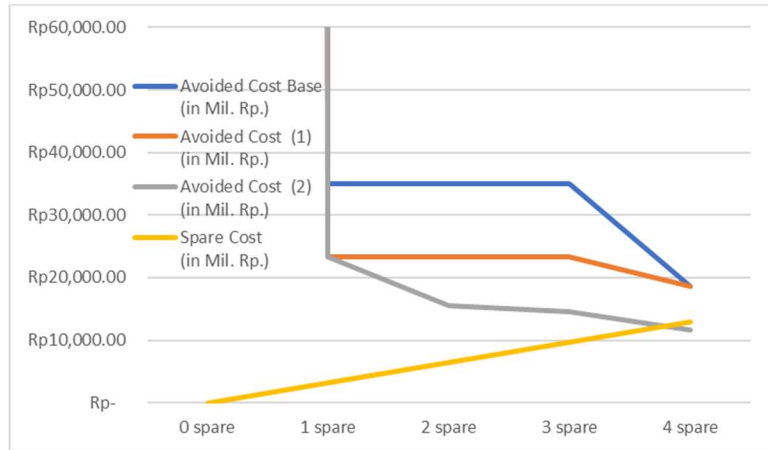Figure 11. Bekasi 500-kV substation results

Figure 12. Cibinong 500-kV substation results

Based on the above results, the spare number is 2 (corresponding to the Kembangan and Bekasi results) and the location of each spare is in Cawang and Cibinong (corresponding to the small effect of Bekasi and Gandul reliability on spare location variation). The Cawang and Cibinong must have a follow up on reducing the disturbance, because its problem cannot be solved with spare provision. The next results for 500-kV Substation in West Java in Figures 13-16.

Figure 13. Cibatu 500-kV substation results

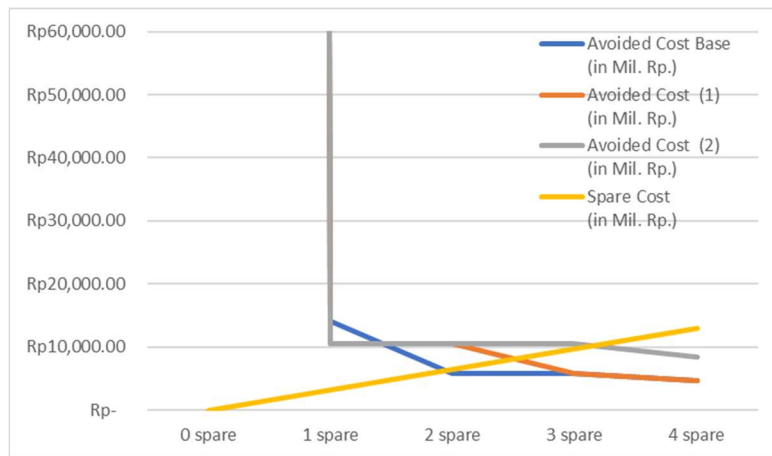Figure 14. Cirata 500-kV substation results

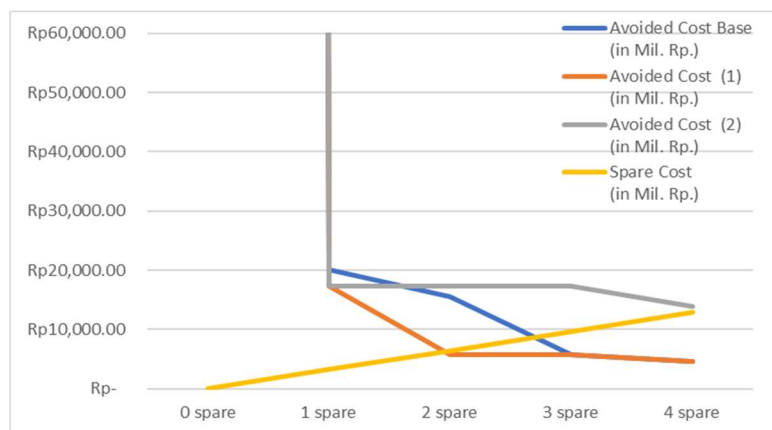Figure 15. Bandung Selatan 500-kV substation results

Figure 16. Mandirancan 500-kV substation results

Based on the above results, the spare number is 2 (corresponding to the Mandirancan results) and the location of each is in Mandirancan (corresponding to location variation 1), and Cirata (corresponding to the small effect of Cibatu reliability on spare location variation). The Cirata must have a follow up on

reducing the disturbance, because its problem cannot be solved with spare provision. The next results for 500-kV Substation in Central Java in Figures 17-18.

Based on the above results, the spare number is 2 and the location of each is in Ungaran and Pedan. Based on the Pedan results, both spares should be located in Pedan, but the effect on Ungaran will be greater if the location of each is in Pedan and Ungaran. The 3 spares provision will be too high and redundant. The next results for East Java in Figure 19.
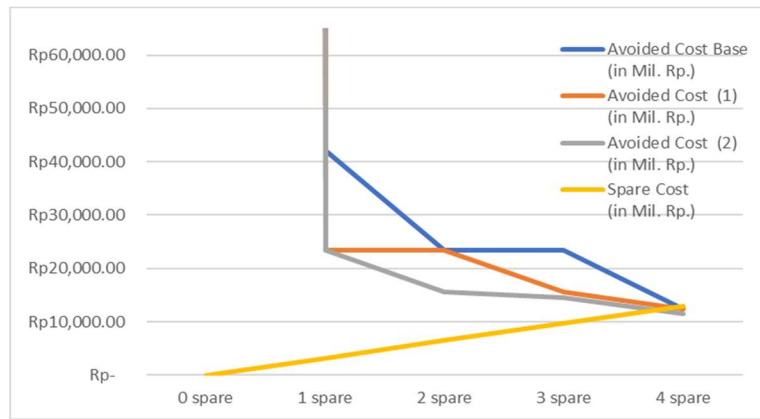
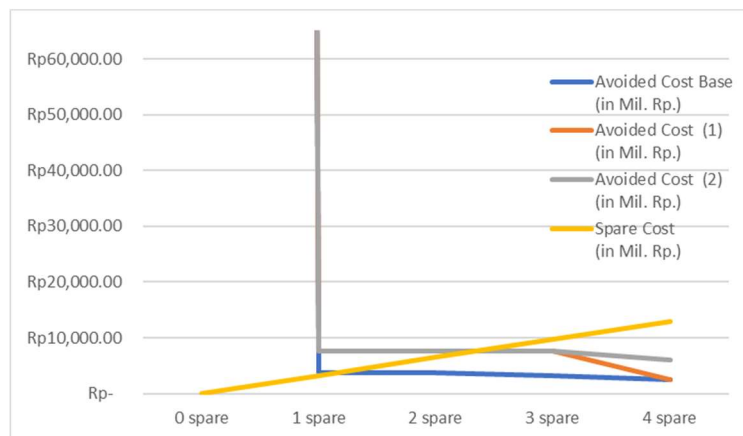Figure 17. Pedan 500-kV substation results
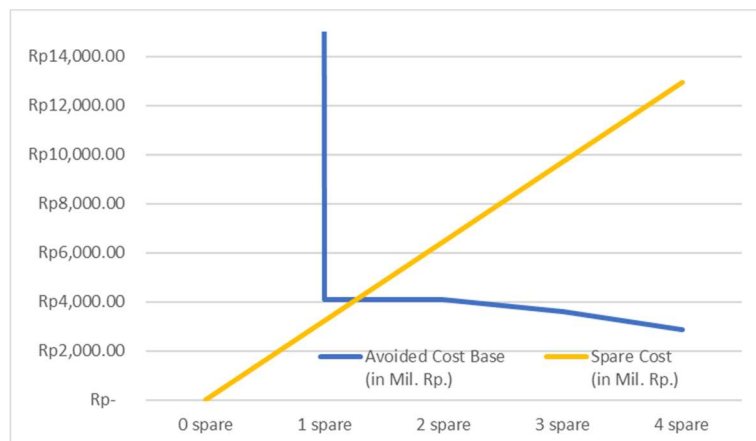
Figure 18. Ungaran 500-kV substation results

Figure 19. Krian 500-kV substation results

4.6. Discussion

These results give two major revelation regarding transformer spare, especially in Java-Bali system. First revelation is optimal number of spare transformer number, the idea of increasing spare transformer number will not increase significant reliability, and there are certain limit of spare transformer number. Therefore, some investment cost could be saved if the spare transformer number is limited. Second revelation is the effect of location variation to maintain reliability of each substation show that with the optimum way of putting the spare transformer could maintain reliability of overall system reliability, these aspects currently overlooked by other research.

5. CONCLUSION

Markov chain gives the best calculation to determine the number and location of spare transformer by varying every possible combination. Markov Chain model in every 500 kV substations gives clear reliability results based on the variation above. Most of the current studies have not clearly consider the spare location output, on the other hand this research finds the opportunity to maintain the system reliability by changing the installation rate. This installation rate defines the location of spare transformer. Based on the calculation results, there are significant effect on system reliability if the spare number and location could be determined by this method. Economic criteria give better determination of spare number and location, instead of reliability measure standalone as the criteria.

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