American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-13, Issue-2, pp-118-127
www.ajer.org
Research Paper Open Access

Power Flow Analysis and Voltage Stability Enhancement with Static Var Compensation on South Sulawesi Power Grid

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ABSTRACT : *The purpose of a power flow study is to determine the voltage, phase angle, active and reactive power of each buses in the power grid. This study investigates the power flow in the South Sulawesi power grid that cause changes related to the operation of the 75 MW Sidrap Wind Farm or Pembangkit Listrik Tenaga Bayu. The Newton-Raphson method, one of the most popular methods for power flow is used for numerical calculations. This calculation is done in the environment of MATLAB for 33 buses. The calculation results show that the largest voltage change occurred on the Poso bus that is by 0.03 in per-unit. All buses experienced a phase angle shift, with the Poso bus also showing the largest shift by 43.580 degrees. The highest line losses of approximately 4.638 MW occurred on the line 18-19 Talassa to Geneponto transmission line, with total losses significantly reduced by 2,282 MW. It needs 30 MVAR installed at bus number 3 to improve voltage stability. These results were obtained by determining Poso as swing bus.*

KEYWORDS: *power flow, newton-raphson, static var compensation, south sulawesi.*

Date of Submission: 03-02-2024 Date of acceptance: 14-02-2024

I. INTRODUCTION

1.1 Background

The need of power system development is determined by the economic operation of power system and efficient investment scheduling and also must be based on appropriate planning. The study of power flow is the basis of electrical energy system development. The power flow study calculates the voltage, current, power factor, active and reactive power at various buses in an electrical system under normal conditions, both for present operation and for expected operation to occur in the future. Trend research is very important when planning future system development. For successful operation, it is important to understand the impact of connections to other power grid systems, newly installed loads, new power plants and transmission lines prior to installation [1-4].

The latest development of South Sulawesi power grid system is the operation of the Wind Farm or Pembangkit Listrik Tenaga Bayu (PLTB) located in the Pabalesan Mountains, Mattirotasi Tashi Village, Watan Pulu District, and Sidrap Regency. The Sidrap PLTB connection with a capacity of 75 MW will definitely impact South Sulawesi's power system. In the document of PLN RUPTL 2016-2025: 449 [5], Sidrap PLTB is planned as one of the power plants in South Sulawesi. Therefore, an updated power flow study is needed to serve as a comparison and evaluation for the operation of 75 MW Sidrap PLTB in the power grid of South Sulawesi.

1.2 Previous Study

To solve the power flow equation, assume that the power system is in equilibrium. Four parameters are assigned to each bus: voltage magnitude |V|, phase angle δ, active power P, and reactive power Q. Buses are divided into the following categories: 1) slack or swing bus where the voltage |V| and phase angle δ is known, 2) load bus where active power P and reactive power Q are known, and 3) generator bus where phase angle δ and active power P are known [6-9]. There are several methods to solve the power flow equation, for instance

Gauss-Seidel method, Newton-Raphson method, fast the couple method and others. All methods have been proven to works well and correct [10-13].

Performing power flow analysis using the Gauss-Seidel method provides fast and accurate results according to I Putu S A, (2004)). However, it is only suitable for power systems with a small number of busbar. Firdaus and Susanto, F. (2014) conducted a study on power flow research in South Sulawesi and West Sulawesi using the Electric Power System Analysis Program (ETAP). Meanwhile, A.M. Shiddiq Yunus et al., 2014 discusses the power flow in the electrical interconnection system of the South Sulawesi grid [14, 15-19].

1.3 Objective

The main objectives of this research are:

- Calculate the voltage, phase angle, active power, and reactive power of each bus of the South Sulawesi power interconnection system related to the operation of the Sidrap 75 MW PLTB.
- Calculate of line losses in transmission lines.
- Determine the static var compensator to improve voltage stability on the grid system of South Sulawesi.

II. THEORETICAL REVIEW

2.1 Newton-Raphson Method

In an interconnected system with n buses, if P_k and Q_k are known, the voltage on each k bus can be calculated using the following formula:

$$V_k = \frac{1}{V_{kk}}\left(\frac{P_k - jQ_k}{V_k^*} - \sum_{n=1}^{N} Y_{kn}.V_n\right) \tag{1}$$

Here, $n \neq k$.

For a particular bus where voltage is specified instead of reactive power, the real and imaginary components of voltage are determined by first calculating the value of reactive power [20-23]. From equation (1), one can get:

$$P_k - jQ_k = \left(Y_{kk}.V_k + \sum_{n=1}^{N} Y_{kn}.V_n\right) \times V_k^* \tag{2}$$

If $n = k$ then:

$$P_k - jQ_k = V_k^* \sum_{n=1}^{N} Y_{kn} V_n \tag{3}$$

$$Q_k = -\operatorname{Im}\left\{V_k^* \sum_{n=1}^{N} Y_{kn} V_n\right\} \tag{4}$$

The process of solving linear algebraic equations like this is called iteration (Stevenson Jr, 1990: 184-185). Application of Newton-Raphson method can be performed using bus voltages and transmission line admittances in polar or rectangular form. If in polar form then:

$$V_k = |V_k|\angle\delta_k \qquad V_n = |V_n|\angle\delta_n \qquad Y_{kn} = |Y_{kn}|\angle\theta_{kn} \tag{5}$$

So then:

$$P_k - jQ_k = \sum_{n=1}^{N} |V_k V_n Y_{kn}| \angle(\theta_{kn} + \delta_n - \delta_k) \tag{6}$$

$$P_k = \sum_{n=1}^{N} |V_k V_n Y_{kn}| \cos(\theta_{kn} + \delta_n - \delta_k) \tag{7}$$

$$Q_k = -\sum_{n=1}^{N} \left| V_k V_n Y_{kn} \right| \sin(\theta_{kn} + \delta_n - \delta_k) \tag{8}$$

Although the values of P_k and Q_k are known, nevertheless values of V_k and δ_k are not known yet, except the value of slack or swing buses. Nonlinear equations of equation (7) and (8) can be decomposed into a series of simultaneous linear equations by specifying the relationship between active power change ΔP_k and reactive power ΔQ_k with respect to voltage change ΔV_k and phase angle change $\Delta \delta_k$ as follows [24-25]:

$$\begin{vmatrix} \Delta Pk \\ \Delta Qk \end{vmatrix} = \begin{vmatrix} J1 & J2 \\ J3 & J4 \end{vmatrix} \begin{vmatrix} \delta k \\ Vk \end{vmatrix} \tag{9}$$

The elements of the Jacobian matrix can be calculated using equations (7) and (8) at each iteration step, starting from the estimation of the initial voltage and phase angle values. Based on the difference between the set value and the calculation result, changes in active power ΔP_k and reactive power ΔQ_k can also be calculated using the inverse method iteratively. The iterative process then continues until the set tolerance is reached [26].

2.2 Power Flow And Losses of Line Transmission

After calculating the iterative solution for the bus voltage, the next step is to calculate the power flow and losses in the transmission line. Notice the transmission line that connects bus *i* and bus *j* below [27-28]:

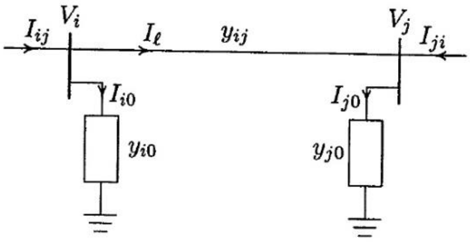


Figure.1. Transmission Line Model for Power Flow Calculation

Line current which flow through bus *i* is defined by the positive polarity of direction of *i* → *j* as follows:

$$I_{ij} = I_l + I_{i0} = y_{ij}\left(V_i - V_j\right) + y_{i0} V_i \tag{10}$$

On the other hand, line current which flow through bus *j* is defined by the positive polarity of direction of *j* → *i* as follows:

$$I_{ji} = -I_l + I_{j0} = y_{ij}\left(V_j - V_i\right) + y_{j0} V_j \tag{11}$$

Complex power S*ij* from bus *i* to *j* and also S*ji* from bus *j* to *i* are express as follow:

$$S_{ij} = V_i I_{ij}^* \tag{12}$$

$$S_{ji} = V_j I_{ji}^* \tag{13}$$

This means that the losses of line transmission can be express in algebraic summation as follows:

$$S_{Lij} = S_{ij} + S_{ji} \tag{14}$$

2.3 Static Var Compensation

Circuits and loads in power system, in addition to conductor resistance, always contain reactance. Transmission lines, for example have series inductance and shunt capacitance which are affected by circuit length, conductor size and spacing. In long lines these quantities may became significant [29-30]. Also, most loads for instance electric motor, transformer, etc, have reactance so that there is a reactive component in the current supplying the load. The total current can be expressed by its in phase and out of phase components called real and reactive, respectively.

The real powers in Watts are:

Single phase case: Watts = E × I × cos Θ
Three phase case: Watts = 1,732 × E × I × cos Θ

The reactive powers in Var are:

Single phase case: Var = E × I × sin Θ
Three phase case: Var = 1,732 × E × I × sin Θ

Various methods are used to supply var needed in a power system, these are shunt reactors, shunt capacitors, series capacitors, synchronous condensers and static var compensators. Static var devices do not provide the real power input provided by the inertia of synchronous condensers when frequency disturbance occur. The choice between static and rotating devices to supply var requirements will be based on capital costs of installation, maintenance cost, losses and the need for inertial support.

III. RESULT AND DISCUSSION

3.1 Method

This research is a simulation using a digital computer. Several computer programs have been developed to perform power flow studies but this study uses MATLAB program. The program used to complete the power flow is *lfnewton*. It has been implemented with *lfybus*, *busout, and lineflow* (Hadi Saadat: 1998) and has been tested with IEEE 30 bus systems and 41 sections of transmission lines. The procedure stages are:

- Data preparation includes bus data and line data based on the single line diagram of South Sulawesi grid system in normal conditions.
- Newton-Raphson power flow calculations are performed by determining base values, accuracy, acceleration factors, and maximum iterations for full-load operating scenarios.
- Initial values for each bus must be entered in the bus data file.
- Once the complete data is prepared, the program can be executed.
- The results are displayed on the computer screen.

The choice of bus data file format is customized to accommodate all the required bus information in each column: voltage |V|, phase angle δ, active power *P* and reactive power *Q* including the shunt capacitor. Each bus must be assigned a code, that is, 1 for slack or swing buses, 2 for generator buses, and 0 for load buses. In the same way, the line data file format must be adapted to the need for transmission line parameters: resistance *R*, reactance *X* and half of *line charging susceptance* ½ *B* in per-unit according to MVA base and transformer tap settings.

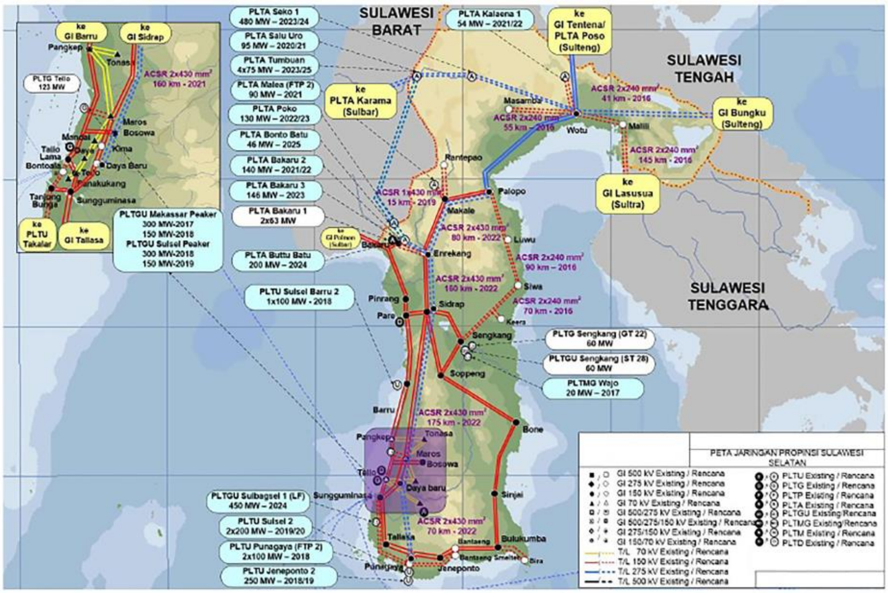


Fig.1. South Sulawesi Power Grid
Source: RUPTL PLN 2016-2025

3.2 Result And Discussion

Power flow solution in this research is done by selecting Poso bus as slack or swing bus. This is because Poso is the farthest generating bus from Makassar as load center. The following calculation results show the voltage ratio and phase angle of different buses of South Sulawesi power grid with and without Sidrap 75 MW PLTB interconnection.

```
Solution by Newton-Raphson Method
    ---  Without PLTB Sidrap     With PLTB Sidrap    ---------

    Bus  Voltage  Angle          Voltage  Angle      Nominal
    No.  Mag.(pu) Degree         Mag.(pu) Degree     Voltage kV

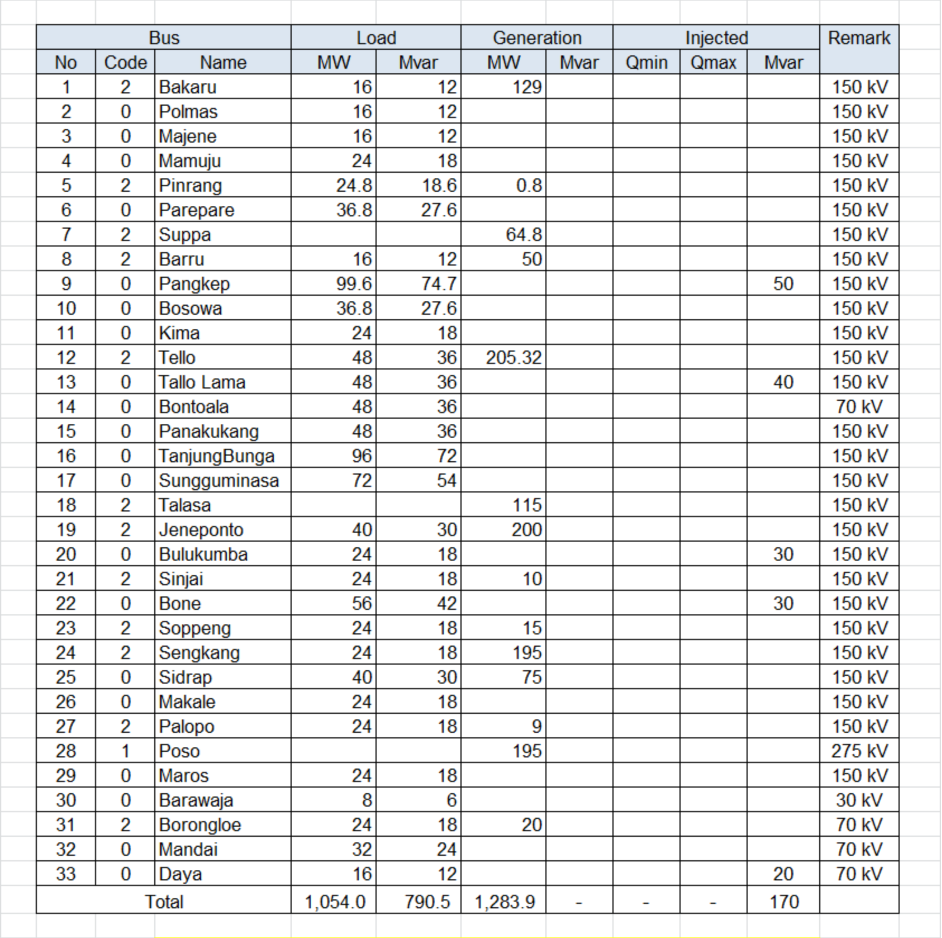
     1   1.090    0.000          1.090    8.630      150
     2   1.031   -0.240          1.032    6.230      150
     3   0.993   -1.981          0.994    4.492      150
     4   0.926   -5.183          0.927    1.294      150
     5   1.010    1.854          1.010    6.870      150
     6   1.020    2.740          1.022    5.993      150
     7   1.030    3.128          1.030    6.402      150
     8   1.030   -0.548          1.030    2.257      150
     9   1.028   -5.409          1.028   -3.077      150
    10   1.050   -5.674          1.050   -3.377      150
    11   1.044   -5.478          1.044   -3.191      150
    12   1.070   -5.164          1.070   -2.922      150
    13   1.141   -5.661          1.141   -3.419      150
    14   1.121   -6.134          1.121   -3.891       70
    15   1.066   -5.326          1.066   -3.084      150
    16   1.035   -5.173          1.035   -2.996      150
    17   1.053   -4.233          1.054   -2.056      150
    18   1.070   -0.569          1.070    1.563      150
    19   1.030    7.325          1.030    9.267      150
    20   1.025    4.901          1.025    6.697      150
    21   1.010    3.168          1.010    4.792      150
    22   1.002    3.416          1.002    4.943      150
    23   1.010    5.564          1.010    6.949      150
    24   1.030    7.525          1.030    8.855      150
    25   1.011    5.266          1.016    6.485      150
    26   0.976   20.775          1.002    1.539      150
    27   1.010   27.415          1.010    0.465      150
    28   1.030   43.580          1.000    0.000      150
    29   1.006    3.122          1.012    4.530      150
    30   1.067   -5.292          1.067   -3.049       30
    31   1.010   -5.096          1.010   -2.821       70
    32   1.013   -5.528          1.013   -3.230       70
    33   1.012   -5.515          1.012   -3.229       70
```

It can be seen on the solution, that the bus voltages is a range of value between 0,096 – 1.141 per unit in which the changes is at bus number 2, 3, 4, 6, 17, 25, 26, 28 and 29. The biggest change is in the bus number 28 with reduction of 0.03 per unit. However, all buses have a phase angle δ shift or displacement. The largest displacement occurred at bus number 28 with a value of 43,580 degrees. At the same time, the flow of active power *P* and reactive power *Q* between the busbar also change depend on total power produced by the generator as follows:

```
Without PLTB Sidrap 75 MW
       Slack/Swing             ------Load------    ---Generation---   Injected
       No Bus          Total     MW       Mvar       MW       Mvar       Mvar
       28 Poso                1054.000   790.500  1084.232   670.548   170.000

With PLTB Sidrap 75 MW
       Slack/Swing             ------Load------    ---Generation---   Injected
       No Bus          Total     MW       Mvar       MW       Mvar       Mvar
       28 Poso                1054.000   790.500  1081.950   663.079   170.000
```

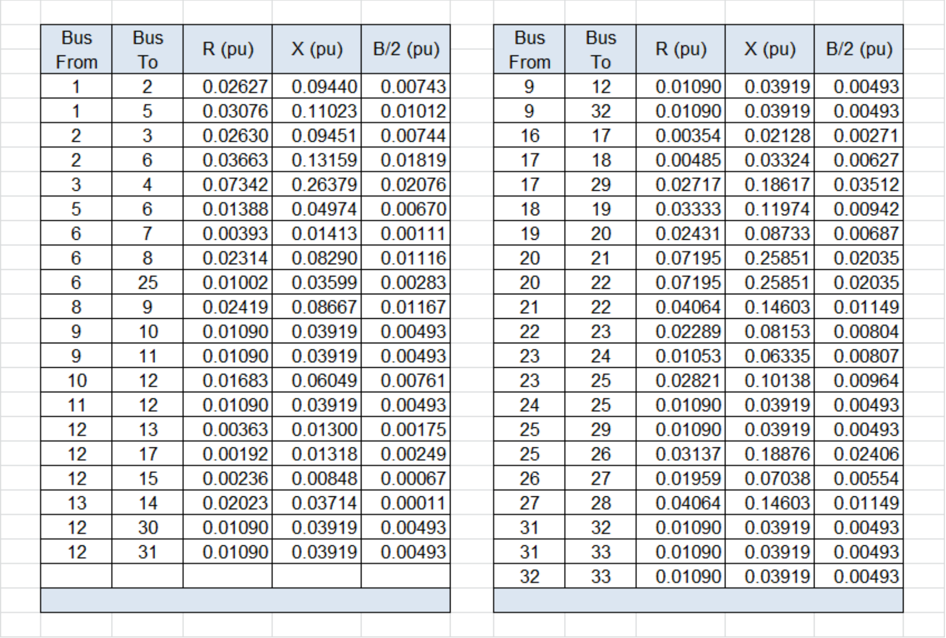
Table 1. Bus Data



Bus			Load		Generation		Injected			Remark
No	Code	Name	MW	Mvar	MW	Mvar	Qmin	Qmax	Mvar	
1	2	Bakaru	16	12	129					150 kV
2	0	Polmas	16	12						150 kV
3	0	Majene	16	12						150 kV
4	0	Mamuju	24	18						150 kV
5	2	Pinrang	24.8	18.6	0.8					150 kV
6	0	Parepare	36.8	27.6						150 kV
7	2	Suppa			64.8					150 kV
8	2	Barru	16	12	50					150 kV
9	0	Pangkep	99.6	74.7					50	150 kV
10	0	Bosowa	36.8	27.6						150 kV
11	0	Kima	24	18						150 kV
12	2	Tello	48	36	205.32					150 kV
13	0	Tallo Lama	48	36					40	150 kV
14	0	Bontoala	48	36						70 kV
15	0	Panakukang	48	36						150 kV
16	0	TanjungBunga	96	72						150 kV
17	0	Sungguminasa	72	54						150 kV
18	2	Talasa			115					150 kV
19	2	Jeneponto	40	30	200					150 kV
20	0	Bulukumba	24	18					30	150 kV
21	2	Sinjai	24	18	10					150 kV
22	0	Bone	56	42					30	150 kV
23	2	Soppeng	24	18	15					150 kV
24	2	Sengkang	24	18	195					150 kV
25	0	Sidrap	40	30	75					150 kV
26	0	Makale	24	18						150 kV
27	2	Palopo	24	18	9					150 kV
28	1	Poso			195					275 kV
29	0	Maros	24	18						150 kV
30	0	Barawaja	8	6						30 kV
31	2	Borongloe	24	18	20					70 kV
32	0	Mandai	32	24						70 kV
33	0	Daya	16	12					20	70 kV
Total			1,054.0	790.5	1,283.9	-	-	-	170	

Source: PT. PLN (Persero) Sulselrabar

Table 2. Line Data



Bus From	Bus To	R (pu)	X (pu)	B/2 (pu)
1	2	0.02627	0.09440	0.00743
1	5	0.03076	0.11023	0.01012
2	3	0.02630	0.09451	0.00744
2	6	0.03663	0.13159	0.01819
3	4	0.07342	0.26379	0.02076
5	6	0.01388	0.04974	0.00670
6	7	0.00393	0.01413	0.00111
6	8	0.02314	0.08290	0.01116
6	25	0.01002	0.03599	0.00283
8	9	0.02419	0.08667	0.01167
9	10	0.01090	0.03919	0.00493
9	11	0.01090	0.03919	0.00493
10	12	0.01683	0.06049	0.00761
11	12	0.01090	0.03919	0.00493
12	13	0.00363	0.01300	0.00175
12	17	0.00192	0.01318	0.00249
12	15	0.00236	0.00848	0.00067
13	14	0.02023	0.03714	0.00011
12	30	0.01090	0.03919	0.00493
12	31	0.01090	0.03919	0.00493
9	12	0.01090	0.03919	0.00493
9	32	0.01090	0.03919	0.00493
16	17	0.00354	0.02128	0.00271
17	18	0.00485	0.03324	0.00627
17	29	0.02717	0.18617	0.03512
18	19	0.03333	0.11974	0.00942
19	20	0.02431	0.08733	0.00687
20	21	0.07195	0.25851	0.02035
20	22	0.07195	0.25851	0.02035
21	22	0.04064	0.14603	0.01149
22	23	0.02289	0.08153	0.00804
23	24	0.01053	0.06335	0.00807
23	25	0.02821	0.10138	0.00964
24	25	0.01090	0.03919	0.00493
25	29	0.01090	0.03919	0.00493
25	26	0.03137	0.18876	0.02406
26	27	0.01959	0.07038	0.00554
27	28	0.04064	0.14603	0.01149
31	32	0.01090	0.03919	0.00493
31	33	0.01090	0.03919	0.00493
32	33	0.01090	0.03919	0.00493

Source: PT. PLN (Persero) Sulselrabar

The total power *P* produced by all generators before and after the Sidrap-PLTB connection is reduced by 2,282 MW, and the power *Q* is also reduced by 7,469 MVar.

Line losses also changes, for overall, transmission line losses is reduced by 2,282 MW, with the highest losses occurred in sections 18-19 and the highest loss reductions in sections 27-28.

```
Highest Losses
Without PLTB Sidrap 75 MW
       Slack/Swing                ------Line Losses-----  Highest Losses    Section
       No Bus        Total           MW      Mvar            MW      Mvar     Line
       28 Poso                     30.232   49.946         4.639   14.589    18-19
With PLTB Sidrap 75 MW
       Slack/Swing                ------Line Losses-----  Highest Losses    Section
       No Bus        Total           MW      Mvar            MW      Mvar     Line
       28 Poso                     27.950   42.477         4.638   14.583    18-19

------------------------------------------------------------------------------


Losses Reduction
Without PLTB Sidrap 75 MW
       Slack/Swing                ------Losses Reduction-----  Section
       No Bus                        MW      Mvar              Line
       28 Poso                     2.209    5.616              27-28
With PLTB Sidrap 75 MW
       Slack/Swing                ------Losses Reduction-----  Section
       No Bus                        MW      Mvar              Line
       28 Poso                     0.029   -2.215              27-28
```

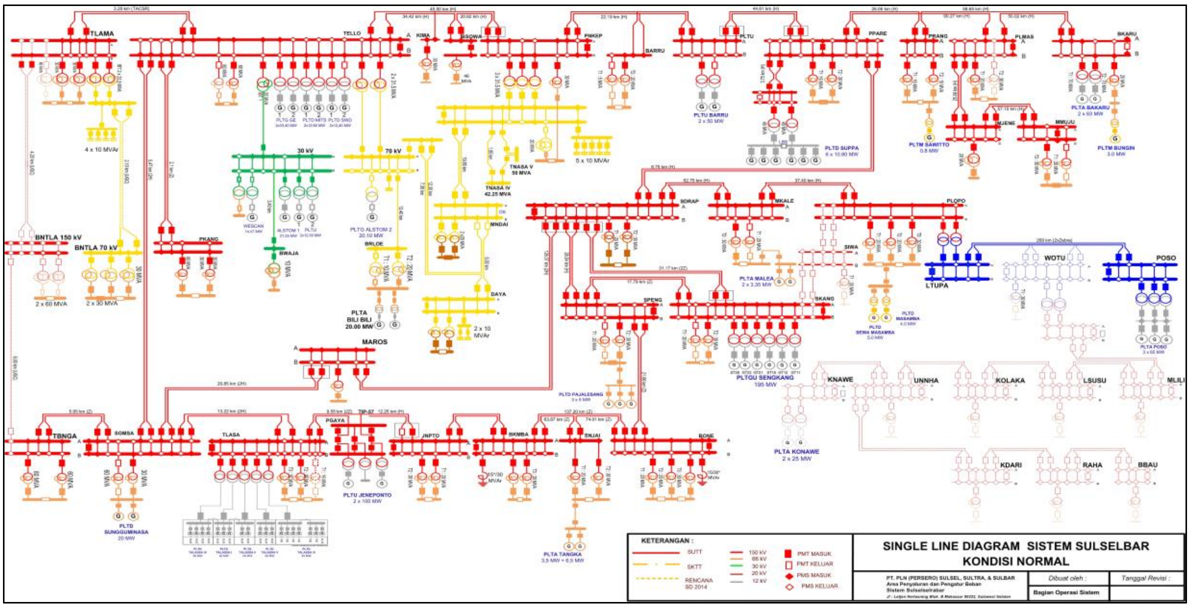


Fig.2. Single Line Diagram of South Sulawesi Power Grid in Normal Condition
Source: PT. PLN (Persero) Sulselrabar

3.3 Voltage Stability Enhancement

It can be seen on the simulation result of power flow Solution by Newton-Raphson Method, there are two buses that have voltage magnitude below 1.0 per-unit value with PLTB Sidrap. The values are 0.994 on bus number 3 and 0.927 on bus number 4. While on bus number 4, the voltage magnitude is change from 0.976 to 1.002 which is fine. The other bus voltage magnitude is in good condition.

To improve the voltage magnitude on bus number 3 and also bus number 4 at least up to its nominal or 1.0 per-unit the used of static var compensator of is then needed. The installation of 30 MVAR static var compensator at bus number 4 is taken into simulation. This will leads to enhance voltage stability.

```
Without VAR Compensation
    ---   Without PLTB Sidrap      With PLTB Sidrap    ---------

    Bus   Voltage  Angle           Voltage  Angle      Nominal
    No.   Mag.(pu) Degree          Mag.(pu) Degree     Voltage kV
     ...
     3    0.993   -1.981           0.994    4.492      150
     4    0.926   -5.183           0.927    1.294      150
     ...
    26    0.976   20.775           1.002    1.539      150

------------------------------------------------------------------------------

With VAR Compensation
    ---   Without PLTB Sidrap      With PLTB Sidrap    ---------

    Bus   Voltage  Angle           Voltage  Angle      Nominal
    No.   Mag.(pu) Degree          Mag.(pu) Degree     Voltage kV
     ...
     3    1.042   -14.077          1.042    4.132      150
     4    1.059   -17.915          1.059    0.295      150
     ...
    26    0.998   -8.328           1.002    1.628      150
```

Based on the solution above, one can say that voltage stability has been enhance because the magnitude of voltage on bus number 3, 4 and 26 are improved to 1.042, 1.059 and 1.002 per-unit, respectively.

The final result of simulation as follows:

```
                   Power Flow Solution by Newton-Raphson Method
                      Maximum Power Mismatch = 1.23379e-07
                             No. of Iterations = 5

    Bus   Voltage  Angle     ------Load------    ---Generation---    Injected
    No.   Mag.     Degree      MW       Mvar       MW       Mvar       Mvar

     1    1.090     8.814    16.000    12.000   129.000   105.783     0.000
     2    1.050     6.187    16.000    12.000     0.000     0.000     0.000
     3    1.042     4.132    16.000    12.000     0.000     0.000     0.000
     4    1.059     0.295    24.000    18.000     0.000     0.000    30.000
     5    1.010     7.052    24.800    18.600     0.800   -75.139     0.000
     6    1.023     6.159    36.800    27.600     0.000     0.000     0.000
     7    1.030     6.584     0.000     0.000    64.800    34.002     0.000
     8    1.030     2.440    16.000    12.000    50.000    19.677     0.000
     9    1.028    -2.898    99.600    74.700     0.000     0.000    50.000
    10    1.050    -3.198    36.800    27.600     0.000     0.000     0.000
    11    1.044    -3.013    24.000    18.000     0.000     0.000     0.000
    12    1.070    -2.744    48.000    36.000   205.320   547.347     0.000
    13    1.141    -3.241    48.000    36.000     0.000     0.000    40.000
    14    1.121    -3.713    48.000    36.000     0.000     0.000     0.000
    15    1.066    -2.906    48.000    36.000     0.000     0.000     0.000
    16    1.035    -2.818    96.000    72.000     0.000     0.000     0.000
    17    1.054    -1.879    72.000    54.000     0.000     0.000     0.000
    18    1.070     1.740     0.000     0.000   115.000    98.650     0.000
    19    1.030     9.442    40.000    30.000   200.000   -34.896     0.000
    20    1.025     6.870    24.000    18.000     0.000     0.000    30.000
    21    1.010     4.964    24.000    18.000    10.000    18.822     0.000
    22    1.002     5.113    56.000    42.000     0.000     0.000    30.000
    23    1.010     7.118    24.000    18.000    15.000   -15.279     0.000
    24    1.030     9.023    24.000    18.000   195.000    46.631     0.000
    25    1.017     6.648    40.000    30.000    75.000     0.000     0.000
    26    1.002     1.628    24.000    18.000     0.000     0.000     0.000
    27    1.010     0.527    24.000    18.000     9.000    38.882     0.000
    28    1.000     0.000     0.000     0.000    -7.662    -5.835     0.000
    29    1.012     4.697    24.000    18.000     0.000     0.000     0.000
    30    1.067    -2.871     8.000     6.000     0.000     0.000     0.000
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31   1.010   -2.643    24.000    18.000    20.000  -148.984     0.000
32   1.013   -3.051    32.000    24.000     0.000     0.000     0.000
33   1.012   -3.050    16.000    12.000     0.000     0.000    20.000

Total                1054.000   790.500  1081.258   629.660   200.000
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IV. CONCLUSION

The power flow solution gives the complex voltages at all the buses and the complex power flows in the lines. It provides information with the node voltage values and their respective phase angles, injected power at all the buses in a connected network hence defining the best location as well as optimum ability of the proposed design of generating station or substation. Conditions of over voltage or over load may occur at power system network and to deal with these problems power flow analysis is an important technique

The conclusion that can be drawn based on the results of power flow and line losses is that with the 75 MW PLTB Sidrap interconnected there is a change in due to changes in the bus voltages |V|, phase angle δ, real power *P* and reactive power *Q* in the South Sulawesi power grid, namely:

a) Changes to the bus voltage magnitude |V| occur on bus number 2, 3, 4, 6, 17, 25, 26, 28, and 29. There was a significant leak on bus number 28, meaning that there were about 0.03 per-units.
b) All buses experience changes in phase angle δ, with the most occurred on bus number 28 of 43,580 degrees.
c) The highest line losses of 4.638 MW occur in sections 18 and 19, the transmission from Tallasa to Jeneponto.
d) The installation of 30 MVAR compensator is needed at bus number 4 to enhance voltage stability.
e) When using bus Poso as a swing or slack bus, total line losses decrease significantly.

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