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MORALITY BEFORE KNOWLEDGE

Critical angle selection for optimal reactive power compensation and active power maximization in stable power systems

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ABSTRACT
Background: At this time electricity problems play an important role in increasing the demand for active and reactive power because the industry is increasing which requires increasing electrical power as well. **Methods:** One of the supporters of overcoming this problem will be an analysis of solving it. It is common for electrical engineering engineers to know about the stability of the power distribution system, which in the following analysis is an analysis of the selection of the critical angle of the power angle. **Finding:** As this power is electrical power which of course consists of active power, reactive power and complex power or apparent power. The three active power, reactive power, and apparent power are directly related to each other, meaning that active power is directly related to reactive power as well as directly related to apparent power. **Conclusion:** So the amount of active power is directly related to the size of the reactive power or directly related to the size of the apparent power. **Novelty/Originality of This Study:** This study presents a novel analytical approach to determining the critical power angle in power distribution systems, highlighting the direct interdependence between active, reactive, and apparent power to enhance system stability in response to increasing industrial electricity demand.

KEYWORDS: critical angle of system stability; optimum active power; reactive power.

1. Introduction

The emergence of electric power is caused by the application of generated voltage and the presence of electric current within electrical devices. Based on this principle, in many electrical systems, the primary focus is on electric power. For instance, people are interested in the power generated by an alternator, the power input to an electric motor drive, or the power transmitted by a radio or television transmitter. Furthermore, in the case of an alternator, if the voltage is a function of time, then the resulting current will also be time-dependent, and its magnitude will be influenced by the components within the electrical device as well as those in the power grid connected to the alternator.

2. Method

The research employs a quantitative and experimental approach to analyze the relationship between voltage, current, and electric power generated in electrical systems, particularly focusing on alternator performance. The study begins with a comprehensive

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literature review to establish a theoretical foundation concerning the principles of electric power generation, the time-dependent behavior of voltage and current in AC systems, and the influence of system components and grid interconnection on current magnitude. Simulation models are developed using tools such as MATLAB/Simulink or ETAP to observe how variations in system parameters—such as load impedance, frequency, and network configuration—affect the output power of an alternator. Experimental data is also collected from a laboratory setup involving a small-scale alternator connected to a variable load, with voltage and current measurements captured using digital oscilloscopes and power meters. The collected data is analyzed to determine the patterns and correlations between time-varying voltage, resulting current, and the magnitude of active and reactive power. Special attention is given to evaluating system stability through parameters such as power angle, power factor, and power-angle (P-δ) curves. This methodology allows for a deeper understanding of how electrical dynamics influence power generation efficiency and system stability, as well as the identification of optimal operating conditions for maximum active power output without compromising system performance.

3. Result and Discussion

3.1 Power in sinusoidal steady state

Based on an idealized condition, for a passive network consisting solely of inductive elements and subjected to a sinusoidal voltage of the form v=Vm sin ωt, the resulting current will have the form i=Im sin (ωt - $\pi/2$), the instantaneous power is then given by p=v.i=Vm.Im (sin ωt)(sin ωt - $\pi/2$). Since sin (ωt - $\pi/2$)=- cos ωt and using the identity 2 sin x cos x=sin 2x, the expression for power becomes p=- ½ Vm.Im sin 2ωt. The resulting waveform is illustrated in Figure 1 below.

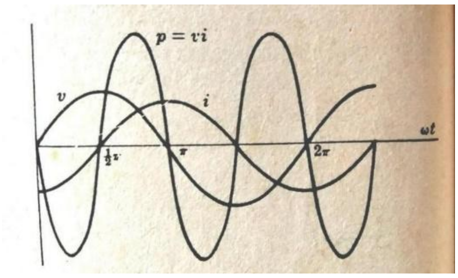

Fig. 1. Voltage, current, and power curves in the network in an ideal state of a purely inductive element

Under ideal conditions, for an active network composed solely of capacitive elements and subjected to a sinusoidal voltage of the form v=Vm sin ωt, the resulting current will have the form i=Im sin (ωt + $\pi/2$), the instantaneous power is thus given by p=v.i=Vm.Im (sin ωt)(sin ωt + $\pi/2$). Since sin (ωt + $\pi/2$)=cos ωt, the power becomes p=v.i=Vm.Im sin ωt cos ωt or equivalently, p=Vm.Im ½ sin 2ωt=½ Vm.Im sin 2ωt. The resulting waveform is illustrated in Figure 2 below.

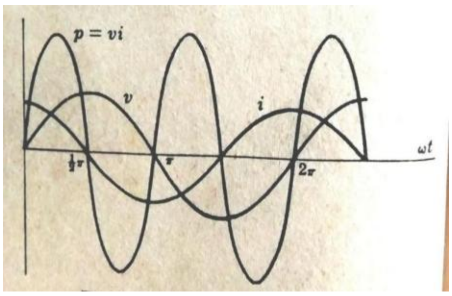

Fig. 2. Voltage, current, and power curves in a network in an ideal purely capacitive state.

Furthermore, under ideal conditions, for an active network composed solely of resistive elements and subjected to a sinusoidal voltage of the form v=Vm sin ωt, the resulting current will be i=Im sin ωt, Thus, the instantaneous power is given by p=v.i=Vm sin ωt Im sin ωt, atau p=Vm.Im sin2 ωt. Using the trigonometric identity sin2x=½ (1 – cos 2x), the power expression become p=½ Vm.Im (1 – cos $2\omega t$). In this case, it can be observed that the power has a frequency twice that of the voltage or current. Moreover, the power is always positive and varies from zero to a maximum value of Vm.Im. The average power is ½ Vm.Im. The resulting waveform is illustrated in Figure 3 below.

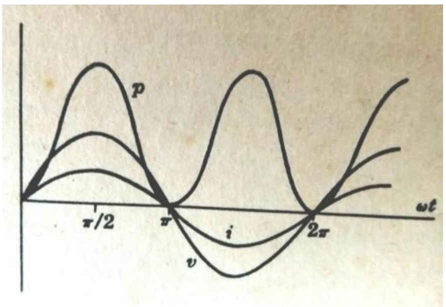

Figure 3. Voltage, current, and power curves in a network in an ideal purely resistive state

2.2 Average power, apparent power, and reactive power

Based on the above formulations, the following statements can be made. First, the power in a network with a purely inductive element is given by p=- ½ $VVVV$sin($2VV$). Second, the power in a network with a purely capacitive element is p=½ $VVVV$sin($2VV$). Third, the power in a network with a purely resistive element is p=½ $VVVVs$(1-cos$2VV$).

Among the three power components, it can be observed that the sinusoidal waveform appears in the power components of inductive and capacitive elements, whereas the power component of a resistive element does not exhibit a sinusoidal form. Therefore, the analysis can be focused on the power components of either inductive or capacitive elements.

Thus, in a general passive network under sinusoidal voltage conditions, by applying the identity sin a.cos a=½ [cos (a-b)–cos (a+b))], and cos -a=cos a, p=½ VmIm [cosθ–cos (2wt+θ)]. The instantaneous power p consists of a sinusoidal term, – ½ VmIm cos (2wt+θ) which has an average value of zero, and a constant term ½ VmIm cos θ. Therefore, the average power is given by P=½ VmIm cos θ=VI cos θ, where V=Vm/√2 and I=Im/√2 are the root mean square (RMS) values of the phasor voltage and current, respectively. This can be expressed in the following equation

$$P=VI\cos\theta \quad \text{(Eq. 1)}$$

The term cos θ is known as the power factor (pf). The angle θ represents the phase angle between voltage (V) and current (I); its value always lies between ±90°. Therefore, cos θ, and consequently the real power P, is always positive. However, to indicate the sign of θ, an inductive circuit—where the current lags behind the voltage—has a lagging power factor, whereas a capacitive circuit—where the current leads the voltage—has a leading power factor. The average power P can also be determined using the relationship P=(1/T)∫pdt. The unit of power is watt (W), and kilowatt (kW) equals 1000 W.

2.2.1 Optimum active power

From the average power value, we have P=½ VmIm cos θ=VI cos θ, where V=Vm/v2 and I=Im/v2 are the root mean square (RMS) values of the phasors V and I respectively. The term cos θ is referred to as the power factor, abbreviated as pf. The angle θ is the phase angle between V and I, which always lies between ±90°. Therefore, cos θ and consequently P is always positive. The corresponding curve can be seen in Figure 4 below.

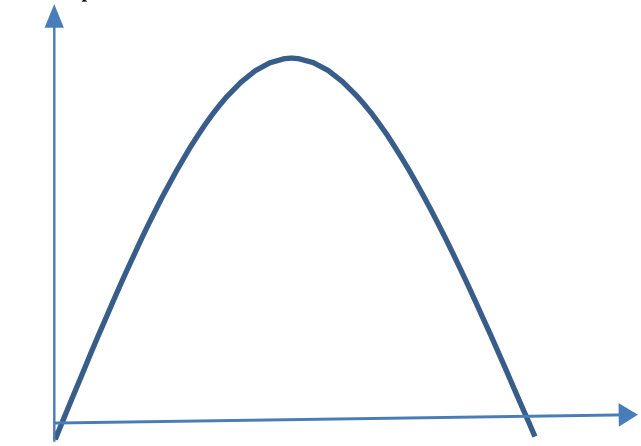

Fig. 4. Optimum active power curve with power factor angle θ

*2.3 Power diagram, rotor shear angle (**δ**), and synchronization power*

The ratio of synchronous reactance (Xs) to resistance (R) in an alternator is relatively insignificant, such that neglecting R introduces minimal error in specific calculations. Therefore, by ignoring R, it is possible to construct a diagram illustrating the relationship between the power delivered by the alternator and the phase angle between the terminal voltage V and the internal generated voltage E. Consequently, it can be deduced that the power delivered is directly proportional to Esinδ\sin\deltaEsinδ, and the graph of power versus rotor displacement angle of the alternator forms a sinusoidal waveform, as illustrated in Figure 5.

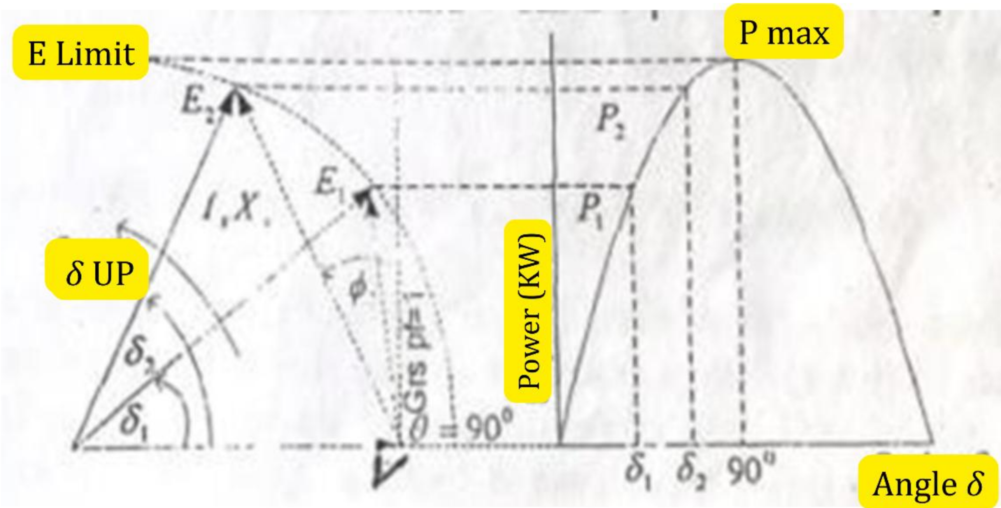

Fig. 5. The relationship between the power and the angle of the generator rotor

Figure 5 can be explained as follows. The length of VE2=I2X, and the length of VP2=VE2 cosØ2=IXs cosØ2, also VP2=E2 sinδ2. Thus, these relationships are applicable for all values of δ and E. Accordingly, E sinδ=IXs cosØ, or I.cosØ=$\frac{Sin\delta}{Xs}$. As previously explained, the power P=VI cosθ or a single-phase system. Here, for this three-phase alternator, P=3 VI cosØ where Ø is the power factor of the generator or the three-phase alternator machine. By substituting the equation I.cosØ=$\frac{Sin\delta}{Xs}$ into the equation P=3 VI cosØ, we obtain P=3. V. $\frac{Sin\delta}{Xs}$ and the phasa-phasa value of the voltage V and the voltage source E are entered 1/√3, So that the equation takes the following form, which indicates synchronism when the angle δ equals the angle $\emptyset$. equation (2) can be applied for all values of rotor displacement angle δ and voltage source E.

$$P=\frac{V \cdot E \ Sin\delta}{Xs} \quad \text{(Eq. 2)}$$

2.4 Stability limits

The stability of a system with interconnected dynamic components refers to the system's ability to return to normal or stable operation after experiencing a disturbance. If the rotor of a synchronous generator exceeds a certain critical angle, the magnetic coupling between the rotor (and the turbine) and the stator weakens or fails. The rotor then loses synchronism with the rotating magnetic field of the stator current and begins to rotate relative to that field, resulting in pole slipping. Figure 6 below illustrates a vector diagram showing the synchronous condition between the motor voltage source E and the generator voltage E, corresponding to a phase angle difference $\emptyset$ between the terminal voltage V and the current I.

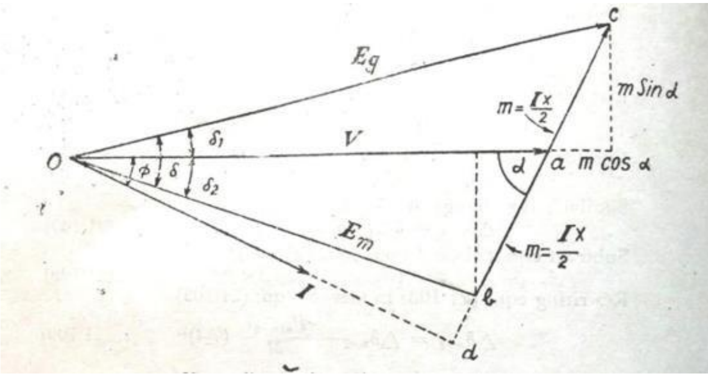

Fig. 6. The relationship between the δ power angle and the $\emptyset$ power factor angle for the motor voltage Em and the generator voltage Eg

The point at which the angle δ equals the angle $\emptyset$ is referred to as the static or steady-state stability limit. In Figure 6, this condition is illustrated by triangle obca, which represents the angle δ, and triangle odao, which represents the angle $\emptyset$, also known as the power factor angle or the phase difference between the terminal voltage V and the current I. When the magnitude of angle δ equals that of angle $\emptyset$, an angle α is formed by the straight line dbac (see Figure 6).

2.4.1 Example of using the equal area criterion to indicate the critical angle δc.

A generator is connected to an infinite busbar and transfers 25 MW of power at synchronous speed. The system reactance is such that the maximum transferable power is 40 MW. Determine the critical angle and the maximum permissible sudden increase in generator output that can be obtained without exceeding the stability limit.

Solution.
Given:
Pmaximum=40 MW PL1=25 MW

The critical angle (δc) and the maximum permissible sudden increase in generator output (PL2) that can be obtained without exceeding the stability limit.

Answer:
PL1 = Pmaximum sin $\boldsymbol{\delta}$1

$\sin \delta 1 \;= \frac{25}{40}$

$\sin \delta 1 \quad = 0.625$

$\text{Or } \delta 1 \quad = \text{shift } \sin^{-1}(0.625) = \text{Reverse sine } (0.625) = 38.7^{o}$

$\delta 1 \quad = \frac{(38{,}7)\,(\pi)}{180} \text{ Radians}$

$\delta 1 \quad = \frac{(38{,}7)\,(3{,}14)}{180} \text{ Radians}$

$\delta 1 \quad = 0.6754 \text{ Radians}$

Pmax is determined for different load angle values, ranging from 0° to 90° (specifically using selected angles: 15°, 30°, 45°, 60°, 75°, and 90°). Based on these varying angles, the power-angle curve can be illustrated as shown in table 1 and figure 7.

Table 1. Power angle curve

δ	Sin δ	P = Pmax sinδ
15^{o}	0.2560	10.24
30^{o}	0.50	20
38.7^{o}	0.625	25
45^{o}	0.707	28.28
60^{o}	0.866	34.64
75^{o}	0.966	38.64
90^{o}	1.0	40

The power is obtained using the equation P=40 sin δ. For example, when the angle δ=90°, then P=40×sin(90°)=40×1=40 MW, and so on for other angles such as 15°, 30°, 38°, 45°, 60°, and 75°. The maximum power (P_{L max}) is 40 MW.

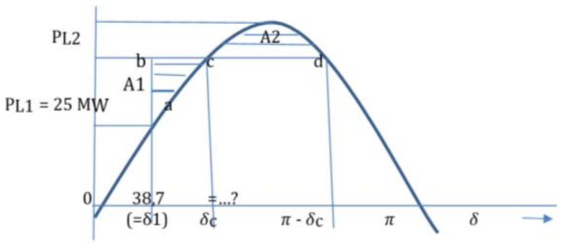

Fig. 7. Generator power output curve and critical power angle

The operating point on the curve is indicated by point a. Subsequently, the load suddenly increases to PL2, causing the rotor to accelerate and oscillate, which is represented by point c on the curve. The maximum rotor swing can reach point d, allowing the generator output to be maintained without compromising system stability (PL2). To ensure the system remains stable, the area A1 must be equal to the area A2.

To solve this problem graphically, point c must be positioned such that the curve areas satisfy A2=A1, resulting in a mathematical determination of the point through integration to calculate the areas. Let the load corresponding to point c be PL2 and the corresponding load angle be δc, implying that PL2 = 40 sin δc (see Equation 3). Subsequently, integration is performed to calculate the areas A1 and A2.

$$A1 = \int_{0{,}6754}^{\delta} (PL2 - 40 \sin \delta)\, d\delta$$
$$A2 = \int_{\delta c}^{\pi - \delta c} (40 \sin \delta - PL2)\, d\delta$$

(Eq. 3)

Since A1=A2, then

$$\int_{0,6754}^{\delta}(PL2 - 40\sin\delta)\,d\delta = \int_{\delta c}^{\pi-\delta c}(40\sin\delta - PL2)\,d\delta$$

(Eq. 4)

This integration can be described in the form of individual integrations as follows.

$$\int_{0,6754}^{\delta}(PL2)d\delta - 40\int_{0,6754}^{\delta}(Sin\ \delta) = 40\int_{\delta c}^{\pi-\delta c}(\sin\delta)\,d\delta - \int_{\delta c}^{\pi-\delta c}(PL2)d\delta$$

(Eq. 5)

$$L2\int_{0,6754}^{\delta}(PL2)d\delta - 40\int_{0,6754}^{\delta} d(-cos\delta) = 40\int_{\delta c}^{n-\delta c}\ldots) - P_{L2}\int_{\delta c}^{\pi-\delta c}\ldots$$

(Eq. 6)

$$PL2\ (\delta)\ \Big|_{0,6754}^{\delta c}\ \Big|_{0,6754}^{\delta c+40\ (\mathrm{Cos}\delta)}\ \Big|_{\delta c}^{\pi-\delta c=40\ (-\mathrm{Cos}\delta)}\ \Big|_{\delta c}^{\pi-\delta c}\ \Big| - PL2\ (\delta)$$

(Eq. 7)

$$PL2(\delta c - 0,6754) + 40(\cos\delta c - 0,6754) = 40\{-\cos(\pi - \delta c) - (-\cos\delta c)\} - PL2\{(\pi - \delta c) - (\delta c)\}$$

(Eq. 8)

As above that PL2=40 sin δc

$$40\sin\delta c\ \ (\delta c - 0,6754) + 40(\cos\delta c - 0,6754) = 40\{-\cos(\pi - \delta c)\} - 40\ \sin\delta c\ \{(\pi - \delta c) - (\delta c)\}$$

$$40\sin\delta c\ \ (\delta c - 0,6754) + 40\sin\delta c\ \{(\pi - \delta c) - (\delta c)\}$$
$$= 40\ \{\cos\ (\pi - \delta c) - (-cos\delta c)\} - 40(cos\delta c - 0,6754)$$

$$Sin\delta c\ (\delta c - 0,6754 + \pi - 2\delta c) = \{-\cos\ (\pi - \delta c) + \cos\delta c\} - \{\cos\delta c - (0,6754)\}$$
$$Sin\delta c\ (-0,6754) + \pi - \delta c) = \cos\ \delta c\ + 0,6754$$
$$(\pi - \delta c - 0,6754)\sin\delta c = \cos\delta c + 0,6754$$

(Eq. 9)

To generate the plot (graph), arbitrary values can be taken for the left-hand side and right-hand side expressions above, with δc assumed to lie between 40° and 80°.

Table 2. Solution (π – δc – 0.6754) sin δc = cos δc + 0.6754

δc	**δ**c in radians (= $\frac{(\delta c).(3,14)}{180}$)	(***π*** – **δ**c – 0,6754)	sin **δ**c	(***π*** – **δ**c – 0,6754) sin **δ**c (Kiri)	cos **δ**c	cos **δ**c + 0,6754 (Kanan)
40	0.6981	1.7681	0.6428	1.135	0.7660	1.4414
50	0.8727	1.5937	0.7660	1.223	0.6428	1.3182
60	1.0427	1.419	0.866	1.225	0.50	1.1754
70	12217	1.2445	0.9397	1.168	0.342	1.0174
80	1.3963	1.0699	0.9848	1.05	0.1736	0.849

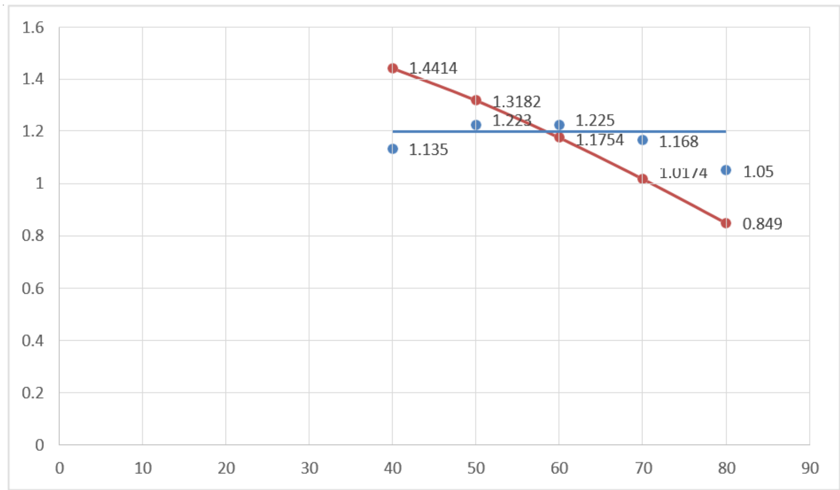

Fig. 8. Curve showing the critical angle δc

By observing the curve in figure 8, the intersections of the left-hand side and right-hand side equations occur at two angles, namely 50° and 60°. Therefore, a detailed breakdown of the critical angle δc within the range of 50° to 60° is made to further examine the precise intersection of the critical angle δc. See Table 3 below.

Table 3. Details of the magnitude of the critical angle δc in the range of 500 to 600

$\boldsymbol{\delta}$c	$\boldsymbol{\delta}$c in radians $(= \frac{(\boldsymbol{\delta}\mathbf{c}).(\mathbf{3,14})}{\mathbf{180}})$	$(\boldsymbol{\pi} - \boldsymbol{\delta}$c – 0,6754)	sin $\boldsymbol{\delta}$c	$(\boldsymbol{\pi} - \boldsymbol{\delta}$c – 0,6754) sin $\boldsymbol{\delta}$c (left)	cos $\boldsymbol{\delta}$c	cos $\boldsymbol{\delta}$c +0,675 (right)
50	0.8722	1.5924	0.7660	1.2197	0.6427	1.3181
51	0.8896	1.575	0.7771	1.2239	0.6293	1.3047
52	0.9071	1.5575	0.7880	1.2273	0.6156	1.2910
53	0.9245	1.5401	0.7986	1.2299	0.6018	1.2772
54	0.942	1.5406	0.8090	1.2463	0.5877	1.2631
55	0.9594	1.5052	0.8191	1.2329	0.5735	1.2489
56	0.9768	1.4878	0.8290	1.2333	0.5591	1.2349
57	0.9943	1.4703	0.8386	1.2329	0.5446	1.2200
58	1.0117	1.4529	0.8480	1.2341	0.5299	1.2053
59	1.0292	1.4354	0.8571	1.2302	0.5150	1.1904
60	1.0427	1.419	0.866	1.225	0.50	1.1754

Thus, to illustrate the magnitude of the angle, Table 4 is provided, presenting the calculations as follows.

Table 4. Calculation to indicate the large angle

$\boldsymbol{\delta}$c	$\boldsymbol{\delta}$c in radians $(= \frac{(\boldsymbol{\delta}\mathbf{c}).(\mathbf{3,14})}{\mathbf{180}})$	$(\boldsymbol{\pi} - \boldsymbol{\delta}$c – 0,6754)	sin $\boldsymbol{\delta}$c	$(\boldsymbol{\pi} - \boldsymbol{\delta}$c – 0,6754) sin $\boldsymbol{\delta}$c (left)	cos $\boldsymbol{\delta}$c	cos $\boldsymbol{\delta}$c + 0,675 (right)
55.0	0.9594	1.5052	0.8191	1.2329	0.5735	1.2489
55.1	0.9611	1.5035	0.8201	1.2316	0.5721	1.2475
55.2	0.9629	1.5017	0.8211	1.2331	0.5707	1.2461
55.3	0.9646	1.500	0.8221	1.2332	0.5692	1.2446
55.4	0.9664	1.4982	0.8231	1.2318	0.5678	1.2432
55.5	0.9681	1.4965	0.8241	1.2332	0.5664	1.2418
55.6	0.9699	1.4947	0.8251	1.2332	0.5649	1.2403
55.7	0.9716	1.493	0.8260	1.2332	0.5635	1.2389

55.8	0.9734	1.4912	0.8270	1.2333	0.5620	1.2374
55.9	0.9751	1.4895	0.8280	1.2333	0.5606	1.2360
56.0	0.9768	1.4878	0.8290	1.2333	0.5591	1.2349
56.05	0.9777	1.4869	0.8295	1.2334	0.5584	1.2338
56.1	0.9786	1.486	0.8300	1.2333	0.5577	1.2331
56.2	0.9803	1.4843	0.8309	1.2334	0.5562	1.2331

After further calculations, the critical angle was found to be at 56.10°. However, a more detailed mathematical refinement is required using Excel iteration within the critical angle interval between 55° and slightly above 56°. The following Table 5 presents the calculations performed using Excel iteration.

Table 5. Calculations with excel iterations

δc	Π – δc - 0,6754	Sin δc	Sin δc*(π–δc –0,6754)	cos δc	cos δc + 0,6754
55	1.506197222	0.819152	1.2338	0.573576	1.249
55.01	1.506022694	0.819252	1.2338	0.573433	1.2488
55.02	1.505848167	0.819352	1.2338	0.57329	1.2487
55.03	1.505673639	0.819452	1.2338	0.573147	1.2485
55.04	1.505499111	0.819552	1.2338	0.573004	1.2484
55.05	1.505324583	0.819652	1.2338	0.572861	1.2483
55.06	1.505150056	0.819752	1.2339	0.572718	1.2481
55.07	1.504975528	0.819852	1.2339	0.572575	1.248
55.08	1.504801	0.819952	1.2339	0.572432	1.2478
55.09	1.504626472	0.820052	1.2339	0.572289	1.2477
55.1	1.504451944	0.820152	1.2339	0.572146	1.2475
55.11	1.504277417	0.820252	1.2339	0.572003	1.2474
55.12	1.504102889	0.820352	1.2339	0.57186	1.2473
55.13	1.503928361	0.820451	1.2339	0.571716	1.2471
55.14	1.503753833	0.820551	1.2339	0.571573	1.247
55.15	1.503579306	0.820651	1.2339	0.57143	1.2468
55.16	1.503404778	0.820751	1.2339	0.571287	1.2467
55.17	1.50323025	0.82085	1.2339	0.571143	1.2465
55.18	1.503055722	0.82095	1.2339	0.571	1.2464
55.19	1.502881194	0.82105	1.2339	0.570857	1.2463
55.2	1.502706667	0.821149	1.2339	0.570714	1.2461

From table 5, the data indicate that the critical angle *δ*_c is indeed at 56.030°, which satisfies the Excel iteration equation: Sin δc (π–δc–0.6754)=cos δc+0.6754, where the values of the left-hand side and right-hand side of the equation both equal 1.2342.

4. Conclusions

The selection of a critical angle in determining the appropriate amount of reactive power supply to achieve optimal active power without compromising system stability can be calculated based on the explanation provided above, and is summarized as follows. First, a power transfer of 25 MW occurs at synchronous speed. Second, the maximum transferable power is 40 MW. Third, the value of the critical angle δc without compromising system stability is 56.030°. Fourth, the generator output that can be obtained without exceeding the stability limit (PL2) is calculated as PL2=Pmaximum×sinδc=40×sin 56.030°=40×0.82933=33.1732 kW.

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