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Innovative Reliability Indices for Optimal Allocation of Renewable Energy in a Rural Power Network

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Abstract: By considering characteristics of rural power system, this study presents an optimal method to estimate wind speed and install Wind Power Turbine (WPT). Entire installation procedure is composed by selecting appropriate buses and verifying the power system after installing WPT. Two innovative indices such as the Power Index in Crisis Time (PICT) and the Endurance Index of Crisis Hours (EICH)) are developed and applied for determining the reliability level of target buses for installing WPT. The stability and reliability of formed hybrid power system are verified by the references of frequency and voltage. Result from this study was applied for a rural power system containing hydro power generation.

Key words: Wind matrix, PICT and EICH indices, system stability and reliability, result application

INTRODUCTION

Weak and small sized power systems widely exist in countryside of developing countries, like China and Indian. Because of rising in prices of traditional energy, renewable energy such as wind and solar power is strongly expect to be introduced to rural power system. However, sometimes it is difficult to manage a rural power system using standard technical stipulations that match for power system of large scaled and high quality.

Such rural power systems are controlled to cut unimportant loads for guarantying other user with power, the systems sometimes operate under the crisis load condition in agricultural irrigation season. Our current research indicates that the existing characteristics of small sized power system are important references in planning and installing renewable energy. Based on such conclusion, several indices derived from system are developed and applied for installing WPT (Litifu *et al*., 2007), in this study two new indices are derived for determining suitable buses to connect WPT. Local wind speed is estimated in the sites covered by power system buses, the system voltage and frequency are tested after WPT are installed. The result of this research may be applied for other rural power systems for installing various kinds of dispersed power sources.

THEORETIC BASIS OF PROCESSING PROCEDURE

Wind and wind power generation matrixes: The processing of initial wind data is very important for installing WPT, valid wind speed over 4.5 m s^{-1} with annual blowing hours about 5000 h are expected, about 30% of valid happening hours on main wind direction is requested for large sized WPT. Estimating precise wind speed needs much work in calculation. However, dispersed wind data is inconvenient for processing and researching, especially for vector calculation in planning of wind generation on a large expected area. Wind vector matrix is therefore, derived by the computing program so that to obtain Generation Matrix, Fig. 1 shows the region under planning; there are 6 sites that are geographical positions of bus 21, 22, 23, 25, 26 and 27 in the rural power system.

In Fig. 1b, the calculation procedure separates original 10 min data into different codes by recorded information and then converted to hourly and monthly average wind speed. Supposing site 5 (bus 21) has the measured wind speed on 5 different direction, they are denoted as v_{51}, v_{52}…v_{55} by using the angle codes given in Table 1, the elements of wind matrix related to site 5 therefore, can be expressed by Eq. 1,

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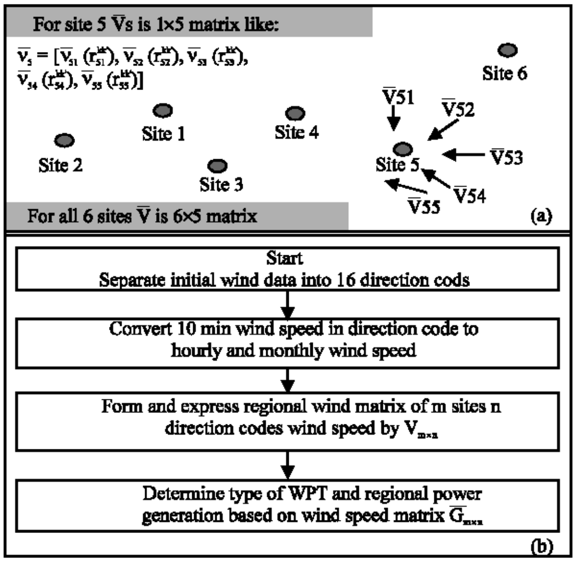

Fig. 1a: The form of wind speed matrix. b: The calculation procedure of wind and generation matrixes

Table 1: Codes sued for wind vector matrix

Degree range	Code	Degree range	Code
0<α(n)≤22.5	(1)	157.5<α(s)≤202.5	(9)
22.5<α(nne)≤45	(2)	202.5<α(ssw)≤225	(10)
45<α(ne)≤67.5	(3)	225<α(sw)≤247.5	(11)
67.5<α(ene)≤90	(4)	247.5<α(wsw)≤270	(12)
90 < α(e)≤112.5	(5)	270<α(w)≤292.5	(13)
112.5<α(ese)135	(6)	12<α(wnw)≤315	(14)
135<α(se)≤157.5	(7)	315<α(nw)≤337.5	(15)
157.5<α(sse)≤180	(8)	337.5<α(nnw)≤360	(16)

$$\begin{cases} r_{ij} = \left[\sum n(kk')/N\right] \times 100\% \\ v_{ij}^{kk'} = (v_1^{kk'} + v_2^{kk'} + \ldots + v_n^{kk'})/n \end{cases} \quad (1)$$

where, r_{ij} is hours ratio of wind speed on angle code kk', n is happened hours on direction kk' and N is general happened hours in all direction, v_1 to v_n is converted hourly wind speed, $v_{ij}^{kk'}$ is hence one element of wind matrix in row i and column j with form of $v_{51}^{kk'}$ as shown in Fig. 1. If one site has wind distributed in n direction, 1×n matrix may be formed, similarly if m sites of a region are under planning; the m×n wind matrix may be formed. Here, n is the maximum number of wind direction; sites that direction number does not reach n are instead by zero in matrix.

In calculation, generation matrix is not only depending on wind matrix but also relating to the type of WPT, the optimal capacity of WPT is determined by Eq. 2:

$$\beta = \frac{P_{WPT}}{A_{WT}} \ [kW/m^2] = k v_j^3 \ [kW/m^2] \quad (2)$$

Equation 2 makes it efficient to select WPT capacity matching for the wind matrix, where, β is wished fraction between WPT and wind speed in unit [kW m^{-2}], A_{WT} and P_{WPT} are blade swept area and expected WPT capacity. Kv_j^3 shows the wind contribution in unit [kW m^{-2}], k relates to air density and power fraction given by k = ρ. c_p/2 and v_j is derived wind speed of site j same as v_5 in Fig. 1.

Now, wind matrix and WPT are estimated and selected. Consequently, there are two methods to form generation matrix, Coefficient Method or Rational Method. Define V as the wind matrix V_0 is Rated Wind Speed Matrix related to output particularity of selected WPT, entire generation matrix and elements may obtained by Eq. 3:

$$\begin{cases} g_{ij} = C_1 v_{ij}^1 + C_2 v_{ij}^2 + \ldots + C_s v_{ij}^s \text{(Coefficient method)} \\ G = KV/V_0 = KVV_0^{-1} \qquad \text{(Rationalmethod)} \end{cases} \quad (3)$$

where, C is coefficient derived from the output character curve, v_{ij} is element of wind matrix to determine g_{ij}. K is rational matrix in unit kW.s/m; V_0^{-1} is inverse matrix of V_0. Generation matrix therefore may be realized by (4):

$$G = \begin{bmatrix} g_{11} & g_{12} & g_{13} & \cdots\cdots & g_{1n} \\ g_{21} & g_{22} & g_{23} & \cdots\cdots & g_{2n} \\ \vdots & \vdots & \vdots & \cdots\cdots & \vdots \\ g_{k1} & g_{k2} & g_{k3} & \cdots\cdots & g_{kn} \\ \vdots & \vdots & \vdots & \cdots\cdots & \vdots \\ g_{m1} & g_{m2} & g_{m3} & \cdots\cdots & g_{mn} \end{bmatrix} \quad (4)$$

In this study, coefficient method is used due to its feasible characters. Equation 4 provides the possible wind power generation from all sites covered by system buses, it is the essential basis to plan and verify whole wind power system in stability and reliability.

Determination of appropriate sites (buses): There is still no standard method to determine the buses for installing WPT, this study proposes dual test method for searching suitable buses for installing WPT and these innovative method shows it's efficient in application.

Power Index in Crisis Time (PICT): Power Index in Crisis Time (PICT) is a criterion to test bus feedings ability under crisis load so as to find weakness level in reliability. PICT is derived from operation statistic data that indicates the available power service and load demand on a target bus under crisis load condition, PICT may therefore, efficiently separate buses into different reliability levels with reliable and credible ways so as to know the bus that most needs supporting from wind power generation. PICT is mathematically defined by (5):

$$PICT_A = \frac{k_{L.A}}{k_{S.A}} \quad (5)$$

where, $k_{L.A}$ stands for the load power constant of bus A with unit $(kW)^{1/2}$ in the crisis period of bus power supply, $k_{S.A}$ indicates the service power constant of bus A with unit $(kW)^{1/2}$ in the crisis period of bus power supply. PICT is therefore, a coefficient responds power service and load of a bus under crisis condition. Power constant $k_{L.A}$ and $k_{S.A}$ can be expressed by Eq. 6:

$$\begin{cases} k_{L.A} = \sqrt{(P_{L.t_1} + P_{L.t_2} + \ldots + P_{L.t_n})/n} \\ k_{S.A} = \sqrt{(P_{S.t_1} + P_{S.t_2} + \ldots + P_{S.t_n})/n} \end{cases} \quad (6)$$

Where, P_S and P_L are active power related to the power service and load that have performed in different time of t_1, t_2,.., t_n, PICT therefore shows an average value. In application, crisis limit is defined, P_L reaching crisis limit will be counted in Eq. 6 even in very short t_i and P_S related to same t_i too. Here, P_L usually has the experienced regularity to follow, in our definition however, $P_{S.A}$ contains system reserved power that is planned to transfer to the target bus. In actual operation, reserved power is hidden and difficult to obtain from historical record. To manage PICT, the bus function should be expanded by equaling it to an isolated power system as shown in Fig. 2.

The equivalent PV and PQ buses in Fig. 2 keep original control habit in frequency and voltage. Since, the elements in Eq. 6 are experienced operation data under system constrains even in critical load period, the bus voltage and frequency are therefore regarded within stability limit. $P_{S.At}$ and $P_{L.At}$ are involved in calculation by considering possible reserved power ΔP_{RE} from system and $\Delta P_{g\cdot RE}$ from generator. Equivalent models can be applied for all buses in system for deriving PICT. Based on resent research (Litifu *et al*., 2006), for a rural power system the bus with PICT $\geq$ 0.95 is regarded as the crisis condition, however, this value may change following load characters and system importance. Figure 3 denotes the track of PICT on bus 25 during 2 h in August, PICT <1 means bus available power supply $P_{S.At}$ (including reserved power) matches for $P_{L.At}$; PICT = 1 shows bus power service being on crisis limit; PICT >1 indicates that the range of $P_{S.At}$ cannot satisfy $P_{L.At}$.

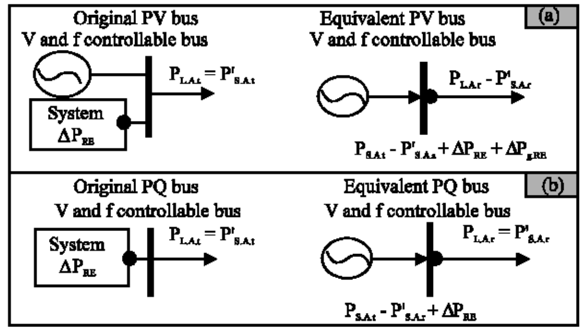

Fig. 2: Basic concept of equivalent models of bus for exterminating PICT of each bus

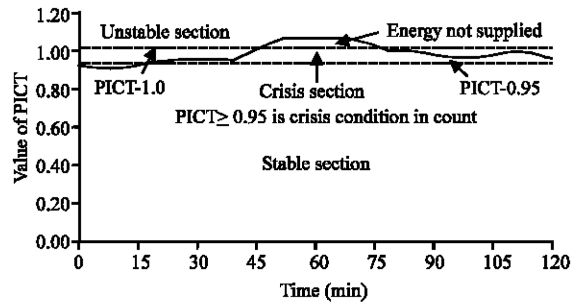

Fig. 3: Two hour's track of PICT on bus 25 on 2nd August

Endurance Index of Crisis Hours (EICH): Endurance Index of Crisis Hours (EICH) is defined as a criterion to indicate the elongation level of crisis time on the target bus. In determination of appropriate bus for WPT installation, only PICT is not enough, actually some buses shows low PICT level but relative high EICH, this situation indicates that although the bus does not suffer from heavy power shortage, its crisis condition may endure a certain long time, the reliability of such bus should be considered. Unstable power sources existing in power system, such as hydro and solar power sources, may increase enduring period, therefore, system generation should be considered in deriving EICH. EICH may be indicated by Eq. 7:

$$EICH = \sqrt{\frac{N_{1.c.h}}{N_{op.h}}} \quad (7)$$

where, $N_{1.c.h}$ is integer number of hours summing from each crisis's time, $N_{op.h}$ is integer number of operation hours during the crisis occurred as expressed by (8):

$$\begin{cases} N_{1.c.h} = \text{int}\left(\sum_{i=1}^{n} \frac{\Delta t_{1.c.i}}{60}\right) \\ N_{op.h} = \text{int}\left(\frac{T_{op.h}}{60}\right) \end{cases} \quad (8)$$

where, $\Delta t_{l.c.i}$, i = 1, 2,.., n is time section in which the crisis load of number i is occurred. In unit of minute, if $\Sigma\delta t_{l.c.i} < 60$ min, it is counted as 1 hour, if $\Sigma\delta t_{l.c.i} = 60$ min, it is divided by 60 to take integer and complement parts as integer hours. $T_{op.h} = t_{l.c.1} - t_{l.c.n}$ is period containing all crisis time, $t_{l.c.1}$ and $t_{l.c.n}$ are starting and finishing time of all crisis condition. The basic principle of EICH on bus 26 in August is shown in Fig. 4. In EICH calculation, the testing period may be daily, monthly and annually or specified period in according to system necessity. In this study, monthly EICH is applied. Especially for a rural power system, character of generation and load should be investigated in deriving EICH, because the load distribution is quite different following seasons of the year. It is essential to take biggest load months as the target in deriving EICH and PICT.

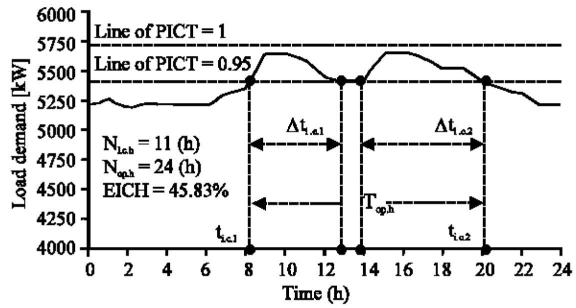

Fig. 4: Basic principle of EICH on Bus 26 on 2nd August

Verification of reliability: Bus reliability is verified by the variation of PICH and EICH before and after installing WPT. The reliability of a power system may be improved after installing WPT as PICH and EICH are tightly related to system generation. In this study, PICH and EICH are respectively simulated by considering practical cases of WPT generation under the rated, average and cut-out wind speed. It is necessary to emphasize that the value of PICH and EICH derived from various level of WPT generation may be represented by full generation; this means the highest level of PICH and EICH on each bus corresponds with the full WPT generation but not beyond that. In this section, PICH and EICH relate to the possibility of full WPT generation is also considered.

Verification of stability: In operation and cut-in process, WPT absorbs reactive power from system; this character may affect bus frequency and voltage and output fluctuation makes other parameters fluctuating, the reason is that the lost reactive power steps down voltage and active power on a bus so that to drop off frequency in certain degree. There is therefore a limit in WPT capacity for any power system. However, fluctuation of electric parameters should be within given margin that usually is taken as limit reference to verify system stability (Alvarado and Tinney, 1991; Stott, 1982). In operation, hybrid system should satisfy Eq. 9:

$$\begin{cases} P_g = P_l + \Delta P_{w.p}, \quad P_g^{min} \le P_g \le P_g^{max} \\ Q_g = Q_l + \Delta Q_{w.p}, \quad Q_g^{min} \le Q_g \le Q_g^{max} \\ V_g^{min} \le V_g \le V_g^{max} \end{cases} \tag{9}$$

where, P, Q and V are system active, reactive power and bus voltage, the maximum and minimum marks stand for the limit of power system, that are usually given. $\Delta P_{w.p}$ and $\Delta Q_{w.p}$ are increased power causing by installed WPT. Here, bus voltage and frequency as well as their fluctuation under cut-in process and normal operation are verified by using the Computation Software of Power Flow and Dynamic Computation Software that was developed specially for the WPT analysis by the members of our research group.

RESULTS AND DISCUSSION

Table 2 shows the capacity of the rural power system under planning to install WPT, Fig. 5 is interconnection of this power system. Bus 12, 14, 19, 20 and 16 are output terminals of power plant, other loads are connected to transformer substations, system buses are with voltage of 6.5, 10 and 35 kV, this power network is mainly located on the plain terrain. Red rings are the buses that wind matrixes are considered.

Table 3 indicates the annual average load and the maximum load experienced on the load buses. In Table 3, S_1, S_3 and S_4 are regular industrial load without serious variation, which locate inside city and supported by PV bus of power plant, they are therefore not considered to install WPT. Load type in Table 3 covers Industry and Processing (Indu. and Pro.), Industry and Living (Indu and Liv), Agriculture and Living (Agri. and Liv.) and Complex Load (Com. Loa.). Agriculture loads buses are taken as main target to install WPT.

Determination of wind and generation matrixes: For 6 sites may form 6×n wind matrixes and generation matrixes (here omitted), n is the number of wind speeds with different direction. To determine the optimal capacity of WPT, one strongest average wind speed is selected from each site to form general generation matrix for bus 21 to bus 27 in order as denoted as follows:

$$\vec{V}_{av} = [6.3_{11}^{09}(16.8),\ 6.8_{12}^{06}(19.2),\ 6.5_{13}^{07}(14.5),$$
$$7.2_{14}^{12}(15.2),\ 6.1_{15}^{11}(18.2),\ 7.2_{16}^{05}(15.9)]$$

Table 2: Characteristic of plants and generators

Gen. No	Rat. Cap. [kW]	x"	Cosφ	Type of plant
G1	2×3000+2000	0.20	0.85	Ther.Plant
G2	2×3600	0.25	0.85	Ther.Plant
G3	2×2500+2000	0.20	0.85	Ther.Plant
G4	2×2500	0.20	0.80	Hyd.Plant
G5	2×3500	0.25	0.80	Hyd.Plant

Table 3: Load characteristic of the rural power system

	Annual Ave. Load		Maximum Load		
Load No.	P[KW]	Q[KVA]	P[KW]	Q[KVA]	Load type
S1	4420	2750	5800	3850	Indu. and Pro.
S3	3850	2200	4600	3150	Indu. and Pro.
S4	4300	2500	5500	3690	Indu. and Pro.
S21	2600	1650	3435	2085	Com. Loa.
S22	1200	750	1650	1050	Agri. and Liv.
S23	1200	750	1585	950	Agri. and Liv.
S25	1500	920	1980	1200	Agri. and Liv.
S26	3800	2350	5520	3050	Agri. and Liv.
S27	3850	2385	6250	3800	Com. Loa.

Table 4: Indices of 3 kinds of WPT and data of 500kW WPT

Target indices	200 kW WPT	300 kW WPT	500 kWWPT
Annual PRUI(%)	34.06	36.90	38.10
Annual PRAI(%)	79.67	82.67	88.00

Pn	Vn	n	*f*n	ηp
500 kW	600 kV	1518 r min^{-1}	50 Hz	0.9
ΔPs [kW]	ΔPr [kW]	ΔPe [kW]	Rs [Ω]	ηg
3.908	5.522	2.732	0.0166	95%

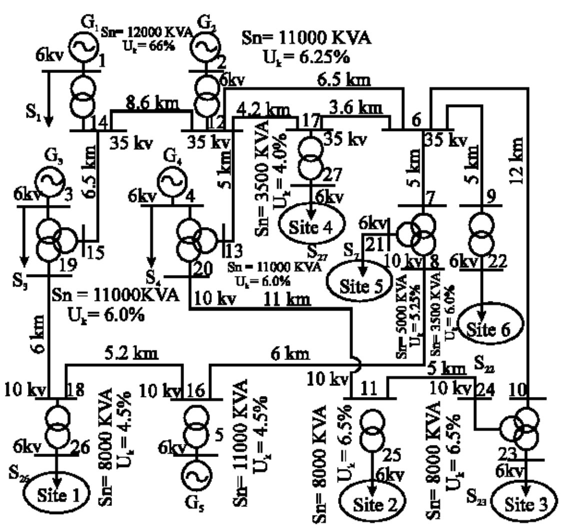

Fig. 5: Interconnection of the target rural power system

This wind matrix is fit for driving large sized WPT like 1000 kW or larger one. However, considering load condition and capacity of system bus, 3 kind of 200, 300 and 500 kW WPT are taken as candidates as shown in Table 4, consider the Percentage Rate of Availability Index (PRAI) and Percentage Rate of Utilization Index (PRUI) 500 kW WPT that is widely used for rural power system is selected. The specification of 500 kW WPT is also shown in Table 4.

Hence, the generation matrix related to 500 kW WPT under average wind speed of wind matrix is shown as follows:

$$G_{av} = [135_{11}, 142_{12}, 138_{13}, 148_{14}, 132_{15}, 148_{16}]$$

Determination of indices of PICT and EICH: Benefiting from maintenance in agricultural slack time, the generation from thermal power plants may averagely reach 85% of total equipment capacity in irrigation season and some generators operate over rated capacity for peak load; but enduring time of such operation is decided by generator mechanical ability. Since, this system contains hydro power plants G_4 and G_5 that available generation tightly depends on the water discharge, the system generation should be considered in order to determine valid reserved power from system to each bus. Total capacity of hydro generator is 14500 kW, to simplify the analysis; all hydro generators are equalized to one hydro generator system. Hydro generation and water discharge is denoted by Eq. 10 (TCDC International SHP, 2001):

$$\begin{cases} Q_{re} = V_{av} S_{av} (1-k_{ef}) \\ P_{re} = \gamma \eta Q_{re} H = \gamma Q H \eta_r \eta_m \eta_k \end{cases} \quad (10)$$

where, V_{av} and S_{av} stand for average speed and section of water flow and pipe. Power fraction $\eta = \eta_v \eta_h \eta_m$ = 62.80% (with Volume η_v = 85%, Hydro η_h = 82% and Mechanical η_m = 90%) and water head is H = 38.5 m. River water discharge changes following the seasons of year as shown in Fig. 6, full water discharge is about 60.2 m^3 s^{-1} that is statistic sum of 5 generators in two hydro plants, the lowest and yearly average water discharge are 37.21 and 50.17 m^3 s^{-1}. Since, water contains red sands, turbine blade is replaced in about 45-60 days. Generators are therefore, maintained in shift even in the period of full water discharge, it is difficult to reach the operational efficiency over 80% of generator capacity even under the maximum load demand.

Based on Fig. 6 and thermal plant data the valid power generation of entire power system is derived and shown in Table 5. Averagely hydro power only contributes 76.68% of its generator capacity from May to October during which the agricultural load may reach the maximum level, entire power system has possibility operating under critical load condition without reserved power and any unexpected generator breakdown may cause the system losing its load.

Based on Table 5, the reserved power for each bus can be decided, the valid power service of each bus in different month is therefore determined. Table 6 shows

Table 5: Monthly valid generation of entire power system (H = Hydro, T = Thermal, G = General. Line loss is contained)

Month order	Jan.	Feb.	Mar.	Apr.
H. Power [kW]	7155	7225	7325	10115
T. Power [kW]	16745	17185	17075	16350
G. Load [kW]	22415	23025	22985	24995
	May	Jun.	Jul.	Aug.
H. Power [kW]	11585	11625	11595	10655
T. Power [kW]	16085	18870	19675	20085
G. Load [kW]	26132	28750	29150	29050
	Sep.	Oct.	Nov.	Dec.
H. Power [kW]	10875	10150	9525	7250
T. Power [kW]	19715	19435	19550	7255
G. Load [kW]	28350	28150	22515	22500

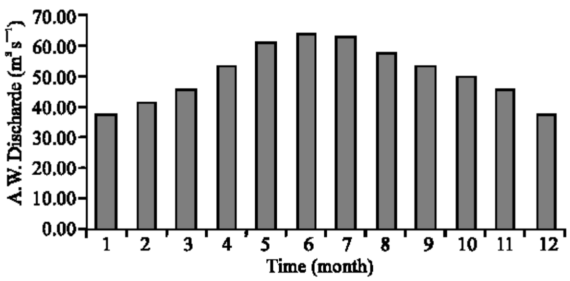

Fig. 6: Estimation of monthly average variation of water discharge from equalized water flow

PICT indices of target buses based on Eq. 5 and 6; buses with agriculture load have relative high PICT in Happened During the Month (HDM). Hourly Valid Serving Power (HVSP) and Hourly Average Power Demand (HAPD) are derived and proposed. Number of Occurred Days (NOD) indicates the days that occurs crisis load condition. Colored buses indicate the highest PICT in order, which may be regarded as the possible candidates to install WPT.

Similarly, the EICH indices of each target buses are derived and shown in Table 7. As explained in previous sections, EICH indices relates to the heavy load months in summer. Accumulated Number of Crisis Hours (ANCH) indicates the total hours in which crisis load condition happens. The meaning of HDM is correspondence with the meaning in PICT. Colored buses indicate the highest EICH in order, which may be regarded as the candidates to install WPT.

Now, the reliability condition on 6 target buses have been identified by Table 6 and 7, Bus 23, 25 and 26 shows high PICT and EICH, the weak reliability that should be improved. Here, although bus 22 shows same EICH as bus 23, the PICT is lower than bus 23; this means bus 23 is much weaker in power supply. The improvement schedule can be determined by listed index order; bus 25 therefore, is the first candidate. In this study, three 500 kW WPT are to be installed respectively on bus 23, bus 25 and bus 26.

Table 6: Simulated results of PICT on each load buses

Bus No.	HVSP[kW]	HAPD[kW]	NOD	HDM	PICT
21	3295	3180	12	9,10,11	0.9824
22	1596	1520	26	9,10,11	0.9758
23	1589	1550	26	6, 7, 8	0.9877
25	1954	1920	38	6, 7, 8	0.9912
26	5693	5610	31	6, 7, 8	0.9927
27	6306	6150	2	9,10,11	0.9875

Table 7: Simulated results of EICH on each load bus with 6~8% of loss in power line

Bus No.	Bus 21	Bus 22	Bus 23
A.N.C.H[h]	96	416	416
H.D.M	9,10,11	9,10,11	6, 7, 8
E.I.C.H[%]	20,97	43.64	43.64
	Bus 25	Bus 26	Bus 27
A.N.C.H[h]	608	496	16
H.D.M	6, 7, 8	6, 7, 8	9,10,11
E.I.C.H[%]	52.76	47.66	8.56

Table 8: Simulated result of PICT and EICH

Bus No.	0 kW	396 kW	1500 kW
PICT under three WPT generation			
Bus 21	0.9824	0.9708	0.94051
Bus 22	0.9758	0.9526	0.89530
Bus 23	0.9877	0.9059	0.86143
Bus 25	0.9912	0.9229	0.88446
Bus 26	0.9927	0.9676	0.95180
Bus 27	0.9875	0.9814	0.96484
EICH (%) under three WPT generation			
Bus 21	20.97	20.84	PICT<0.95
Bus 22	43.64	43.12	PICT<0.95
Bus 23	43.64	PICT<0.95	PICT<0.95
Bus 25	52.76	PICT<0.95	PICT<0.95
Bus 26	47.66	47.05	46.66
Bus 27	8.559	8.533	8.460

Verification of reliability: Table 8 shows that PICT and EICH on each bus have been improved; this means the reliability of entire system is improved too. In simulation, the generation 138 kW (bus 23), 148 kW (bus 25) and 132 kW (bus 26) are related to wind speed of 6.5, 7.2 and 6.1 m s^{-1}, the full generation of 500kW is related to rated wind speed of 12.5 m s^{-1}. EICH of the buses that PICH are lower than 0.95 is not considered as mentioned in previous section. WPT may increase system reserved power with same quantity, which may used to support the buses without WPT based on operational schedule, it is supposed here that 60% of increased power is transmitted to other buses and PICT and EICH on other buses are simulated based on this supposed quantity.

Verification of stability: This verification should cover both of normal and dynamic states of power system. Normal state includes the cut-in process (transient process) and regular operation, dynamic state indicates

Table 9: Simulated results of reduction of power flow (P.F) system voltage and frequency [p.u]

Case 1: P (WPT) = 500kW under wind over 12.5 m s^{-1}		
Red.P.F	22.26% (B.24-B.11)	2.26% (B.20-B.11)
B. to B.	10.52% (B.19-B.18)	2.03% (B.16-B.18)
Bus Vol.	0.9523 (Bus22) = V = 0.9988 (Bus14)	
Bus Fre.	49.9612 (Bus14) = f = 49.9710 (Bus12)	
Case 2: P (WPT) = 138kW under wind about 6.6 m s^{-1}		
Red.P.F	12.76% (B.24-B.11)	2.10% (B.20-B.11)
B. to B.	8.22% (B.19-B.18)	0.00% (B.16-B.18)
Bus Vol.	0.9551 (Bus22) = V = 0.9990 (Bus14)	
Bus Fre.	49.9753 (Bus14) = f = 49.9755 (Bus12)	
Case 3: P (WPT) = 0kW under wind below 3.5 m s^{-1}		
Red.P.F	0.104% (B.24-B.11)	0.218% (B.20-B.11)
B. to B.	0.193% (B.19-B.18)	0.370% (B.16-B.18)
Bus Vol.	0.9530 (Bus22) = V = 0.9981 (Bus15)	
Bus Fre.	49.9781(Bus14) = f = 49.9856 (Bus12)	

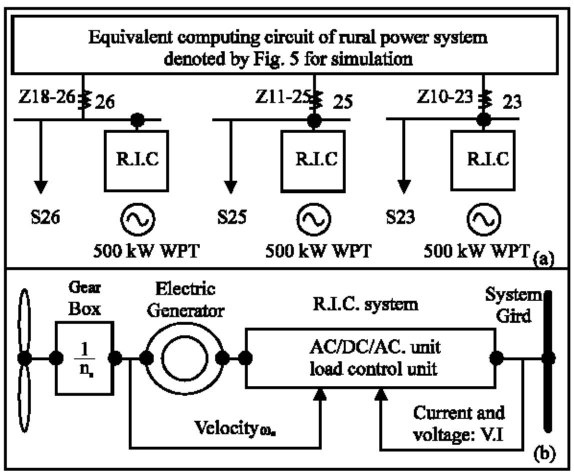

Fig. 7: (a) Simulation circuit, (b) Controlling system of 500 kW WPT with R.I.C (Regulator and Inverter Controller)

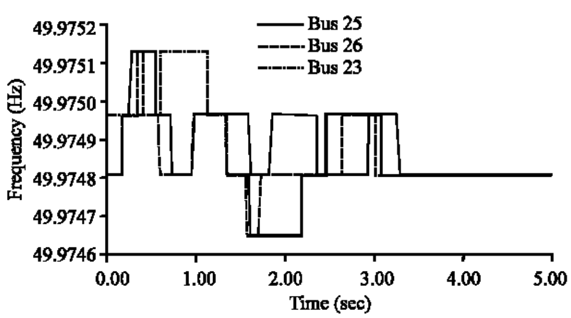

Fig. 8: Frequency fluctuation when WPT on Bus 23, Bus 25 and Bus 26 are cut in rural power system

the condition of faults inside and outside WPT. This study only deal with the verification of normal state, the dynamic state possibly caused from faults can be fixed by protecting system. Figure 7 shows diagram used for simulation of stability verification (value list is omitted).

Voltage and frequency are taken as verification references in simulation, the range of result and fluctuation of each bus should within system allowed margin. In simulation, three WPT generation should be considered: the full generation of 500 kW from each WPT under wind speed 12.5 m s^{-1} or over it; the average WPT generation of 137.33 kW (use 138 kW) from each WPT under the average wind speed of 6.6 m s^{-1} and also the WPT generation under the wind speed below the cut-in wind speed of 3.5 m s^{-1}. If power system is stable under these three WPT generations, it will be therefore, stable under all other WPT generation as shown in Table 9.

In simulation, 100MVA and 6.6KV are taken as the basis of per unit and allowed system margins are given with bus voltage ±5% and frequency ±2%. Table 9 has proved that voltage and frequency are within limit margin, system is therefore, stable after installation of WPT.

Simulation results indicate that the increment of the WPT generation makes system frequency dropping, the reason is that WPT absorbs system reactive power (given negative value in simulation) in operation so as to reduce certain amount of active power, in some heavy cases the capacity compensation is necessary (Chen, 1995). Since, WPT are directly installed on load bus, power flow and line loss on related lines have been reduced as shown in Table 9. Fluctuation in cut-in process is very important in stability verification, Fig. 8 shows the fluctuation of bus frequency when three WPT on bus 23, bus 25 and bus 26 are simultaneously cut in power system by using Dynamic Computation Software; simulated results are also within limited margin proposed above. The voltage fluctuation during the connection process is covered by the values shown in Table 9.

CONCLUSION

The most important point of this research is to solving installation problem of dispersed power unites by entirely inspecting system's particularities. The proposed equations are formed based on WPT application experiment. Wind and Generation Matrixes shows feasible and convenient in calculation, PICT and EICH are proved applicable for rural power system in searching weak buses of reliability. Result application relates to the real case asked by the concerned local power system. It is expected to develop other indices of a small power system based on the idea of this research.

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