STUDY OF USING PARTICLE SWARM FOR OPTIMAL POWER FLOW IN IEEE BENCHMARK SYSTEMS INCLUDING WIND POWER GENERATORS

by
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A Thesis
Submitted in Partial Fulfillment of the Requirements for the
Master of Science Degree

Department of Electrical and Computer Engineering
Southern Illinois University Carbondale
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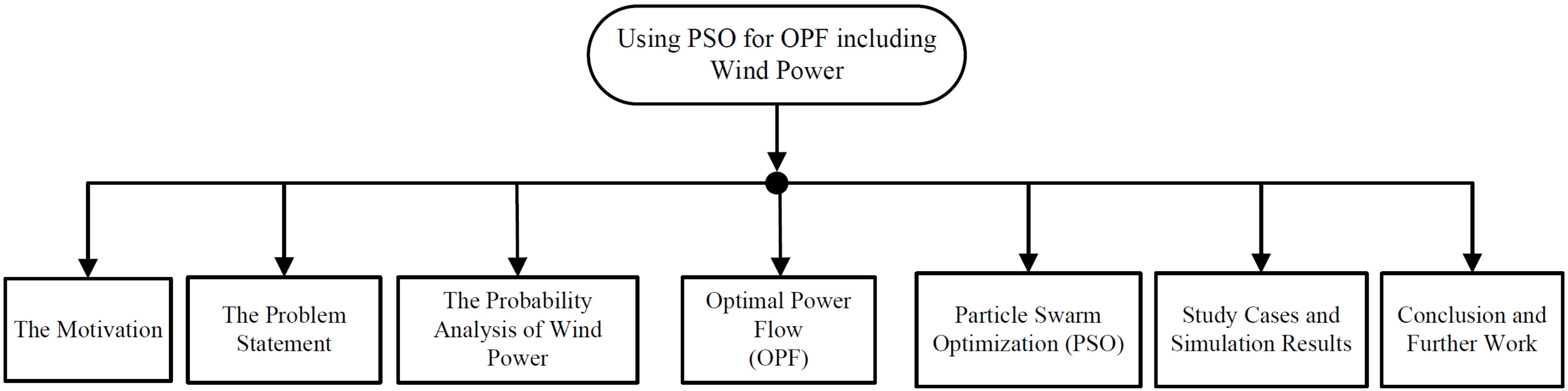
THE OUTLINE


Using PSO for OPF including Wind Power
The Motivation
The Problem Statement
The Probability Analysis of Wind Power
Optimal Power Flow (OPF)
Particle Swarm Optimization (PSO)
Study Cases and Simulation Results
Conclusion and Further Work

The main aim of the thesis is to obtain the optimal economic dispatch of real power in systems that include wind power.

✓Model considers intermittency nature of wind power.

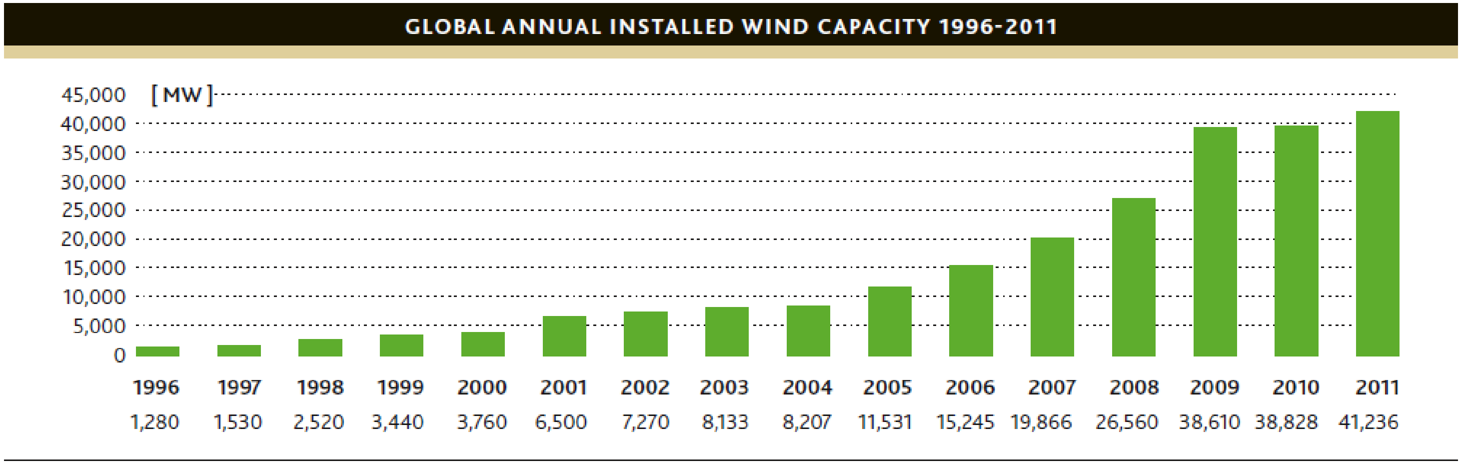
✓ Solve OPF by PSO.

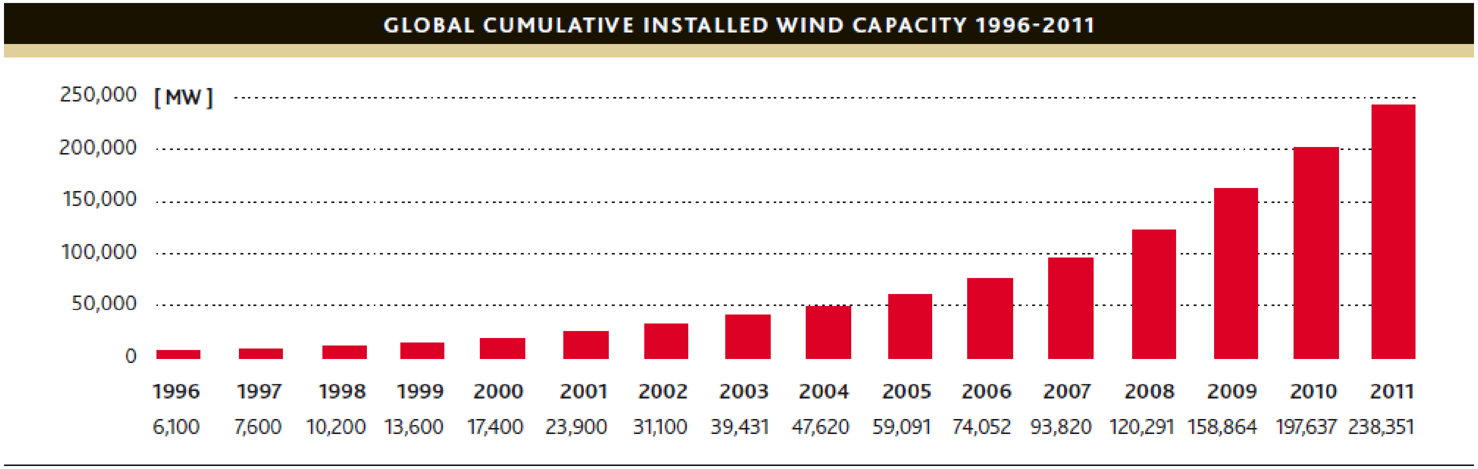
✓ IEEE 30-bus test system.

✓6-bus system with wind-powered generators.

MOTIVATION:

The Growing Importance of Wind Energy:





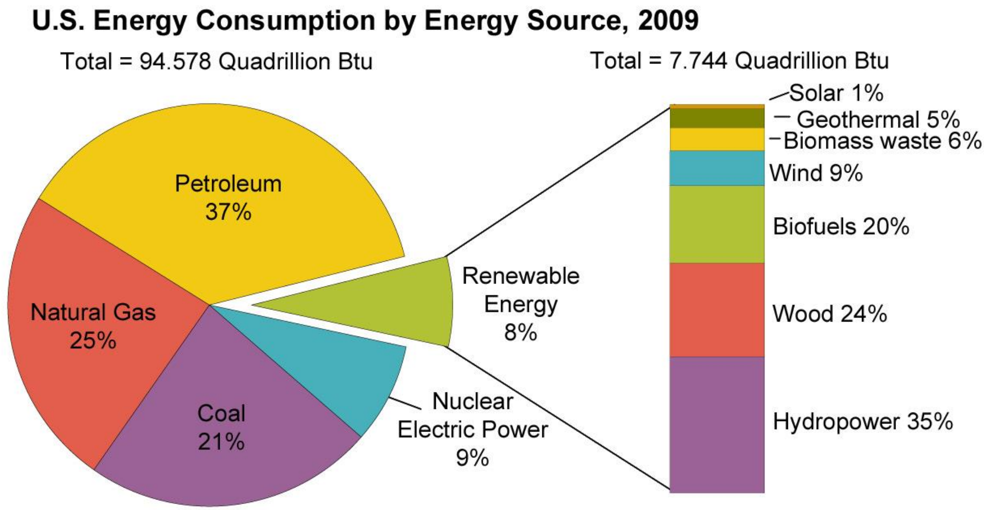
MOTIVATION:

The Cost of Wind Energy:

- Abundance of wind power everywhere;

- Fluctuations of oil prices;

- One of the most competitive renewable resources.

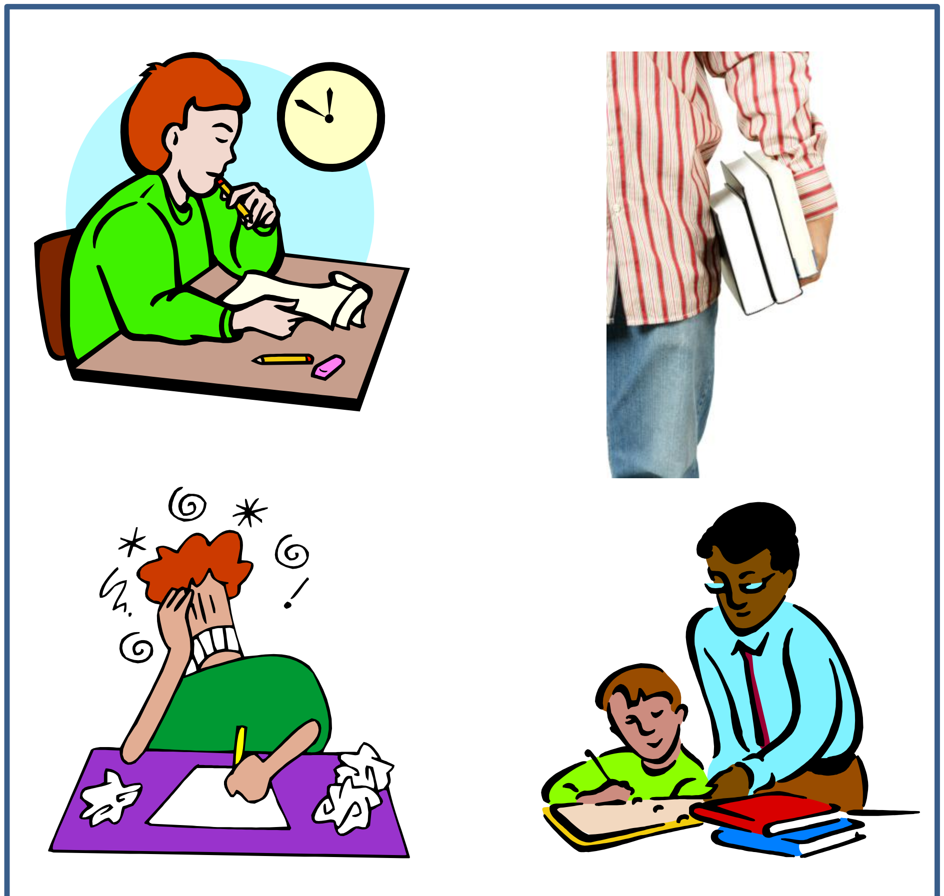


Note: Sum of components may not equal 100% due to independent rounding.
Source: U.S. Energy Information Administration, *Annual Energy Review 2009*, Table 1.3, Primary Energy Consumption by Energy Source, 1949-2009 (August 2010).

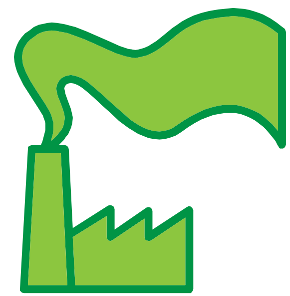
MOTIVATION:

The Optimal Economic Dispatch of Wind Power:

It’s a challenging topic to search about.



Spring 2011



ECE488

Power Systems Engineering

ECE580

Wind Energy Power Systems

STATEMENT OF THE PROBLEM

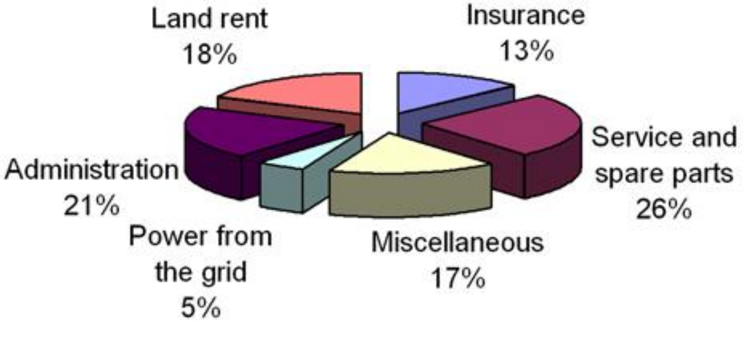
The objective function of the optimization problem in the thesis is to minimize the **operating cost of the real power generation.**

Conventional-thermal generators

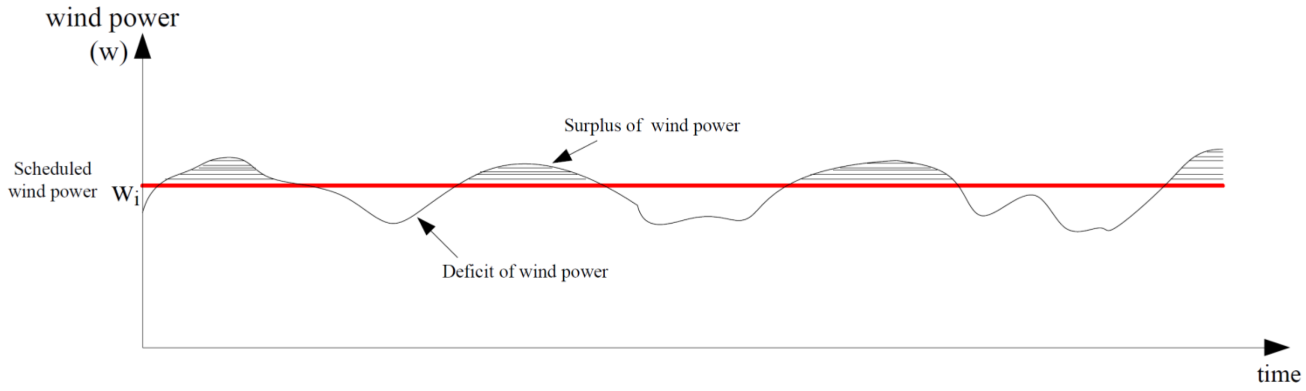
$$C_i = a_i P_i^2 + b_i P_i + c_i$$

Wind-powered generators

$$C_{w,i} = d_i w_i$$



STATEMENT OF THE PROBLEM



$$C_{p,i} = k_{p,i}(W_{i,av} - w_i) \qquad \text{(underestimation)}$$

$$= k_{p,i} \int_{w_i}^{w_{r,i}} (w - w_i) f_W(w) dw$$

Since $f_W(w)$ Weibull probability distribution function (pdf) of wind power.

In similar fashion,

$$C_{r,i} = k_{r,i}(w_i - W_{i,av}) \qquad \text{(overestimation)}$$

$$= k_{r,i} \int_{0}^{w_i} (w_i - w) f_W(w) dw$$

STATEMENT OF THE PROBLEM

The model of OPF for systems including thermal and wind-powered generators:

$Minimize:$

$$J = \sum_{i}^{M} C_i(p_i) + \sum_{i}^{N} C_{wi}(w_i) + \sum_{i}^{N} C_{p,i}(w_i) + \sum_{i}^{N} C_{r,i}(w_i)$$

$Subject\ to:$

$$p_{i,\min} \le p_i \le p_{i,\max}$$

$$0 \le w_i \le w_{r,i}$$

$$\sum_{i}^{M} p_i + \sum_{i}^{N} w_i = L$$

$$V_i^{\min} \le V_i \le V_i^{\max}$$

$$S_{line,i} \le S_{line,i}^{\max}$$

Where:

$$\boxed{C_i = a_i P_i^2 + b_i P_i + c_i}$$

$$\boxed{C_{w,i} = d_i w_i}$$

$$\boxed{C_{p,i} = k_{p,i} \int_{w_i}^{w_{r,i}} (w - w_i) f_W(w)\, dw \quad \text{(underestimation)}}$$

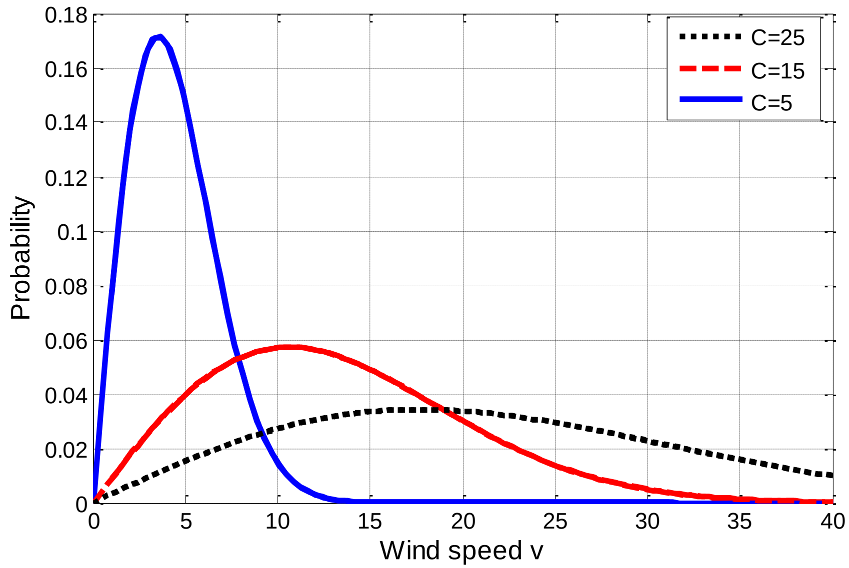
$$\boxed{C_{r,i} = k_{r,i} \int_{0}^{w_i} (w_i - w) f_W(w)\, dw \quad \text{(overestimation)}}$$

Particle Swarm Optimization (PSO) algorithm is used for solving this optimization problem.

PROBABILITY ANALYSIS OF WIND POWER:

The wind speeds in particular place take a form of Weibull distribution over time, as following:

$$f_V(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} (e)^{-(v/c)^k}$$

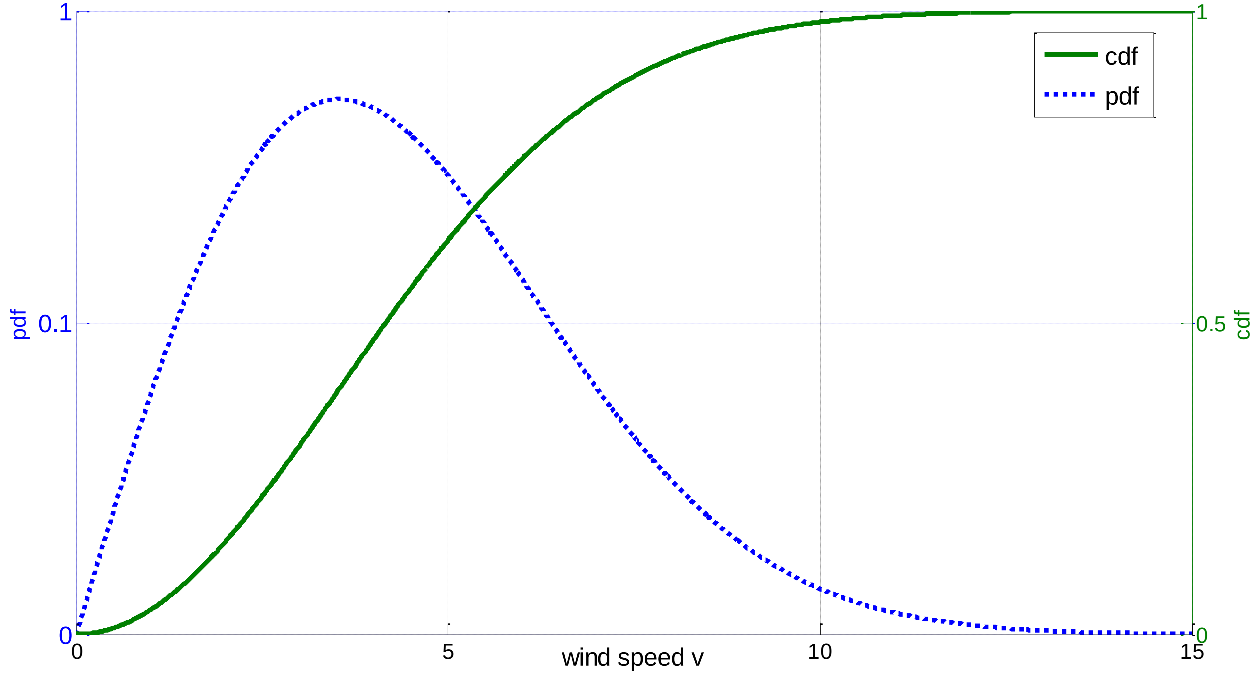


Weibull probability density functions (**pdf**) of wind speed for three values of scale factor **c**

PROBABILITY ANALYSIS OF WIND POWER:

The cumulative distribution function (cdf) of Weibulll distribution is:

$$F_v = \int_0^v f_v(\tau)d\tau = 1 - e^{-(v/c)^k}$$



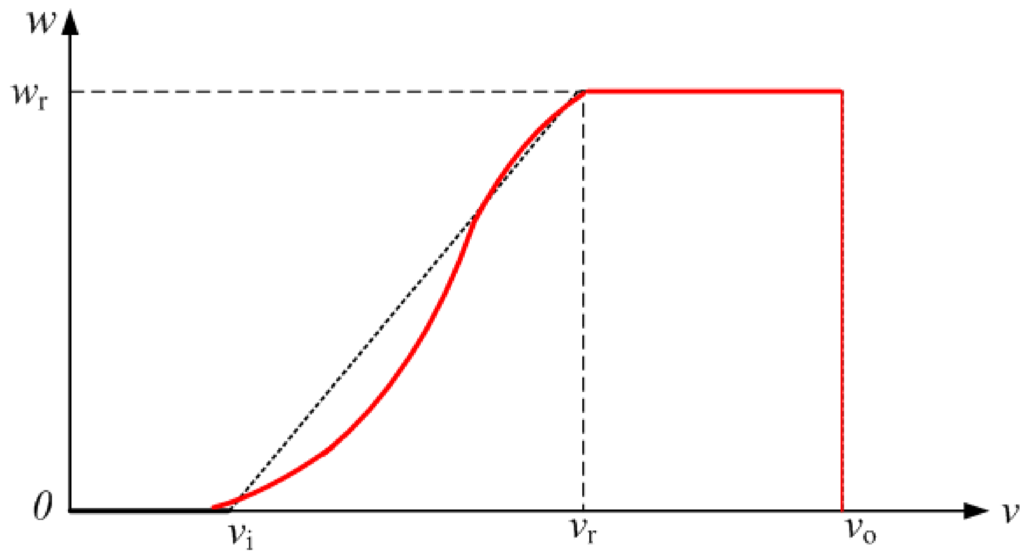
Weibull pdf and cdf of wind speed for c=5 *m/s*

PROBABILITY ANALYSIS OF WIND POWER:

The captured wind power ➔ $P_m = C_p \frac{\rho}{2} A_R v^3$

The captured wind power can be assumed to be linear in its curved portion:

$$w = \begin{cases} 0; & (v < v_i \text{ or } v \geq v_o) \\ w_r \dfrac{(v - v_i)}{(v_r - v_i)}; & v_i \leq v < v_r \\ w_r; & v_r \leq v < v_o \end{cases}$$

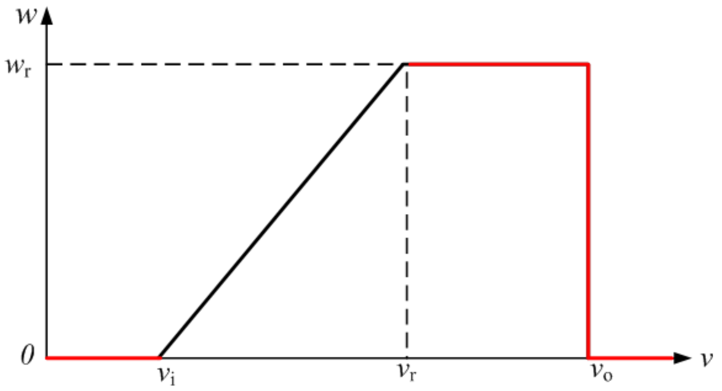


The captured wind power

PROBABILITY ANALYSIS OF WIND POWER:

The linear transformation (in terms of probability) from wind speed to wind power is done as following:

$$\Pr\{W=0\}=1-\exp\left(-\left(\frac{v_i}{c}\right)^k\right)+\exp\left(-\left(\frac{v_o}{c}\right)^k\right)$$



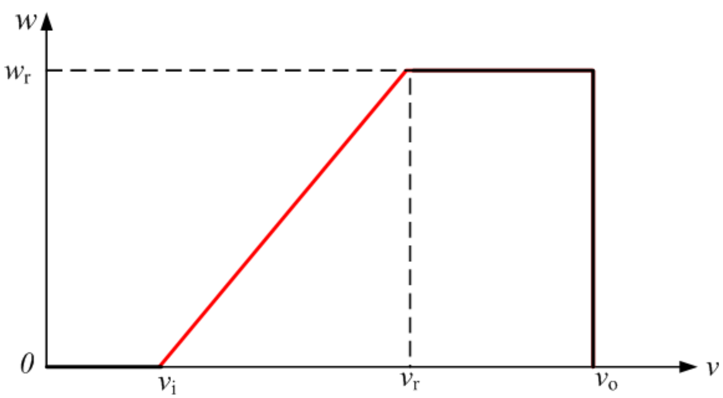
$$\Pr\{W=w_r\}=-\exp\left(-\left(\frac{v_r}{c}\right)^k\right)-\exp\left(-\left(\frac{v_o}{c}\right)^k\right)$$

While for the continuous portion:

$$\boxed{\because\ f_W(w)=f_v\left(\frac{w-b}{a}\right)\left|\frac{1}{a}\right|}$$

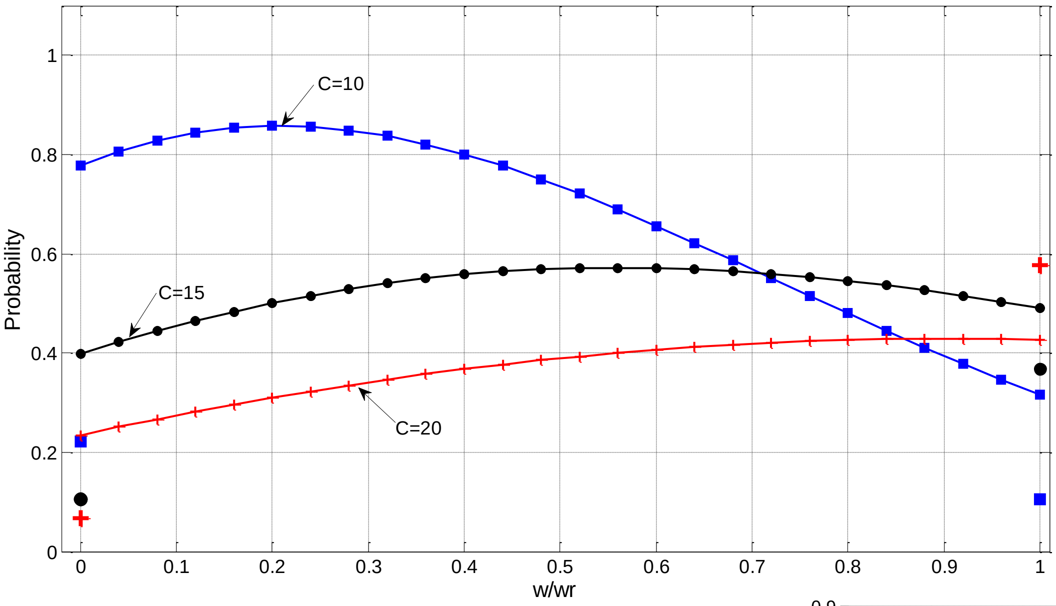
$$f_W(w)=\frac{klv_i}{w_r c}\left(\frac{(1+\rho l)v_i}{c}\right)^{k-1}\exp\left(-\left(\frac{(1+\rho l)v_i}{c}\right)\right)^k$$

$$\text{Where}:\ \rho=\frac{w}{w_r},\qquad l=\frac{(v_r-v_i)}{v_i}$$



PROBABILITY ANALYSIS OF WIND POWER:

Probability vs. Wind power for C=10, 15 and 20

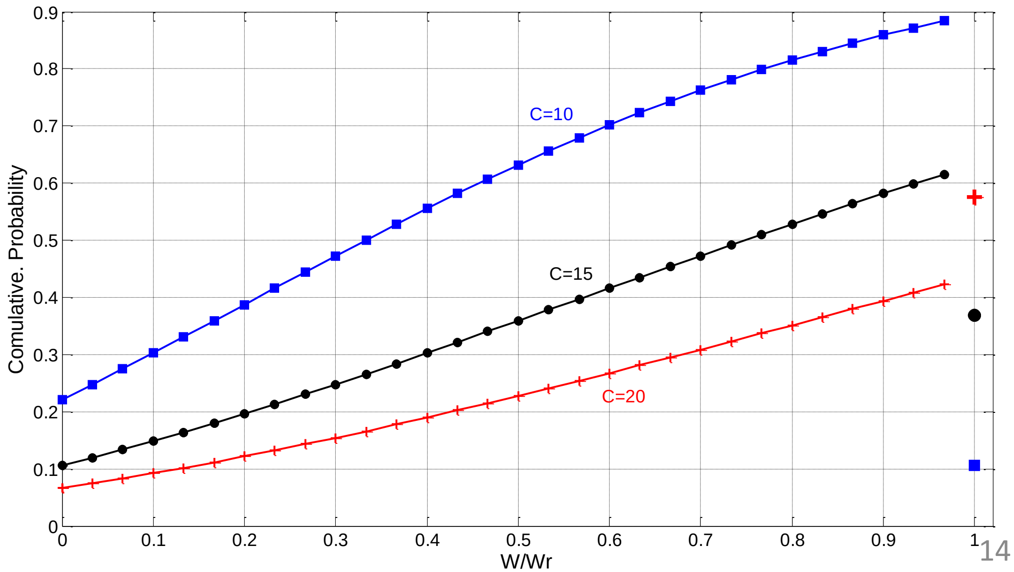


The probability density function pdf of wind power

$$C_{p,i} = k_{p,i} \int_{w_i}^{w_{r,i}} (w - w_i) f_W(w) dw \quad \text{(underestimation)}$$

$$C_{r,i} = k_{r,i} \int_{0}^{w_i} (w_i - w) f_W(w) dw \quad \text{(overestimation)}$$

The cumulative distribution function (cdf) of wind power



PROBABILITY ANALYSIS OF WIND POWER:

Then, plug the transformed wind power equations in the model:

$$\Pr\{W=0\}=1-\exp\left(-\left(\frac{v_i}{c}\right)^k\right)+\exp\left(-\left(\frac{v_o}{c}\right)^k\right)$$

$$\Pr\{W=w_r\}=-\exp\left(-\left(\frac{v_r}{c}\right)^k\right)-\exp\left(-\left(\frac{v_o}{c}\right)^k\right)$$

$$f_W(w)=\frac{klv_i}{w_r c}\left(\frac{(1+\rho l)v_i}{c}\right)^{k-1}\exp\left(-\left(\frac{(1+\rho l)v_i}{c}\right)\right)^k$$

$$C_{p,i}=k_{p,i}\int_{w_i}^{w_{r,i}}(w-w_i)f_W(w)dw$$

$$C_{r,i}=k_{r,i}\int_{0}^{w_i}(w_i-w)f_W(w)dw$$

$$Minimize: J=\sum_i^M C_i(p_i)+\sum_i^N C_{wi}(w_i)+\sum_i^N C_{p,i}(w_i)+\sum_i^N C_{r,i}(w_i)$$

OPTIMAL POWER FLOW (OPF)

The optimal power flow (OPF) is a mathematical optimization problem set up to minimize an objective function subject to equality and inequality constraints.

$$Min: \; J(\boldsymbol{x},\boldsymbol{u})$$

Subject to:

$$g(\boldsymbol{x},\boldsymbol{u}) = 0$$

$$h(\boldsymbol{x},\boldsymbol{u}) \le 0$$

Where:

$$J(\boldsymbol{x},\boldsymbol{u}) = \sum_{i}^{M} C_i(p_i) + \sum_{i}^{N} C_{wi}(w_i) + \sum_{i}^{N} C_{p,i}(w_i) + \sum_{i}^{N} C_{r,i}(w_i)$$

$$\boldsymbol{x}^T = [P_{G1}, V_{L1}, ..., V_{L,NL}, \; Q_{G1}, ..., Q_{G,NG}, \; S_{line1}, ..., S_{line,nl}]$$

$$\boldsymbol{u}^T = [V_{G1}, ..., V_{NG}, \; P_{G2}, ..., P_{G,NG}, \; T_1, ..., T_{NT}, \; Q_{C1}, ...Q_{C,NC}]$$

While: $g(\boldsymbol{x},\boldsymbol{u}) = 0 \;\; \Rightarrow$

$$P_i - V_i \sum_{j=1}^{n} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0$$

$$Q_i - V_i \sum_{j=1}^{n} V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = 0$$

OPTIMAL POWER FLOW (OPF)

On the other hand, for inequality constraints $h(\boldsymbol{x},\boldsymbol{u}) \leq 0$:

Where: Generator Constraints:

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \qquad i = 1, \ldots.., NG$$

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max} \qquad i = 1, \ldots.., NG$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \qquad i = 1, \ldots.., NG$$

Whereas: Transformer Constraints:

$$T_{i}^{\min} \leq T_{i} \leq T_{i}^{\max} \qquad i = 1, \ldots.., NT$$

While: Shunt VAR Constraints:

$$Q_{Ci}^{\min} \leq Q_{Ci} \leq Q_{Ci}^{\max} \qquad i = 1, \ldots.., NC$$

Finally: Security Constraints:

$$V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max} \qquad i = 1, \ldots.., NL$$

$$S_{line,i} \leq S_{line,i}^{\max} \qquad i = 1, \ldots.., nl$$

OPTIMAL POWER FLOW (OPF)

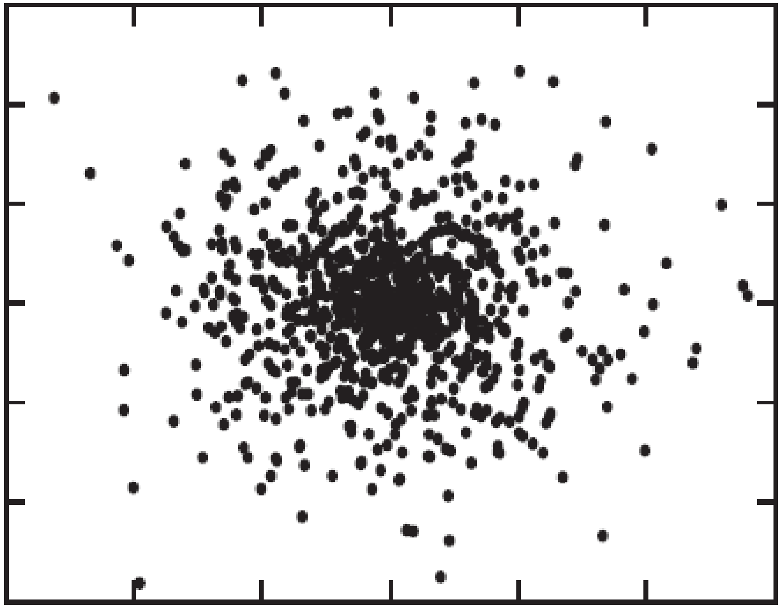
By using penalty function principle, all constraints are included in the objective function $J(\boldsymbol{x},\boldsymbol{u})$:

$$J_{aug} = J + \lambda_P (P_{G1} - P_{G1}^{\lim})^2 + \lambda_V \sum_{i=1}^{NL} (V_{Li} - V_{Li}^{\lim})^2 + \lambda_Q \sum_{i=1}^{NG} (Q_{Gi} - Q_{Gi}^{\lim})^2 + \lambda_S \sum_{i=1}^{nl} (S_{line,i} - S_{line,i}^{\max})^2$$

Where: $\lambda_P, \lambda_V, \lambda_Q$, and λ_S are penalty factors.

PARTICLE SWARM OPTIMIZATION (PSO)

PSO suggested by **Kennedy** and **Eberhart** (**1997**).



PARTICLE SWARM OPTIMIZATION (PSO)

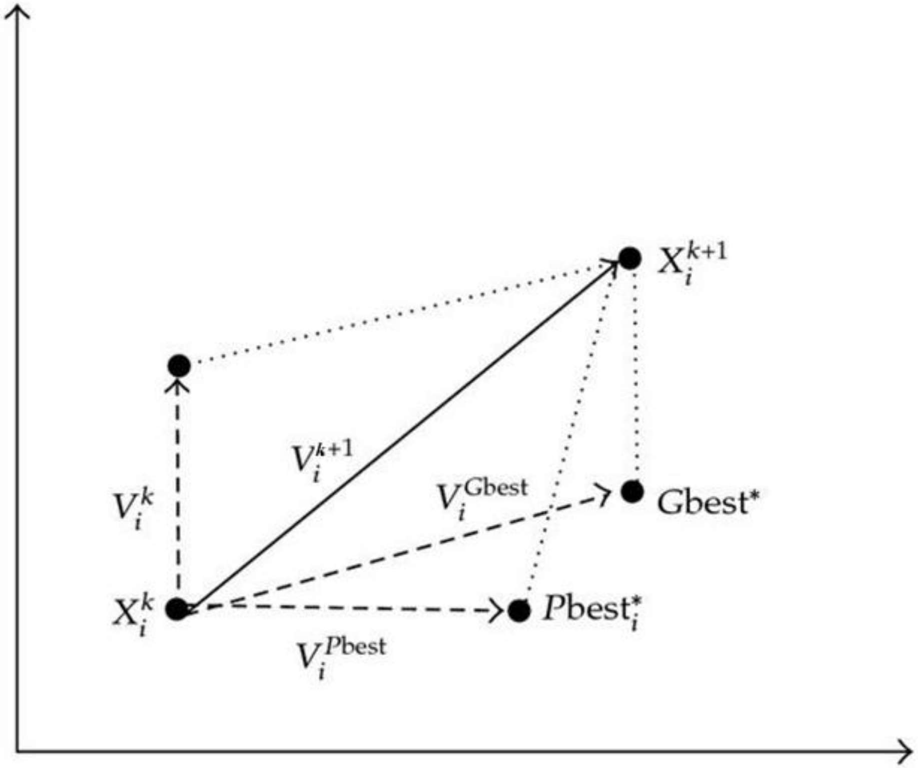
PSO Searching Mechanism:

$$v_i^{k+1} = w * v_i^k + c_1 * U(pbest_i^k - x_i^k) + c_2 * U(gbest^k - x_i^k)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1}$$

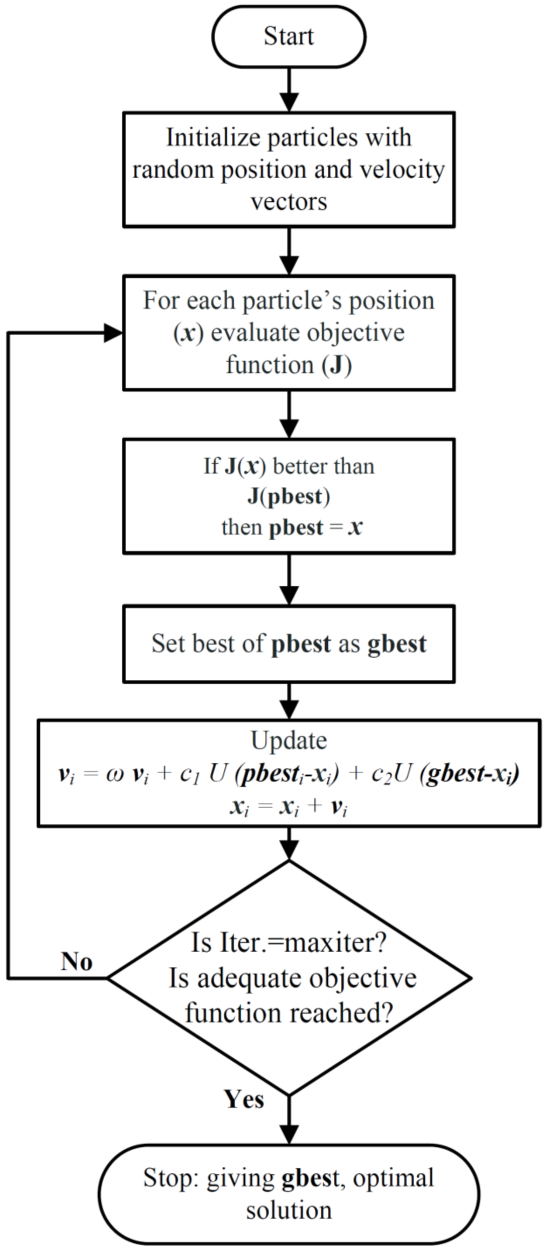
Where:

$$w = w_{\max} + \frac{(w_{\max} - w_{\min})}{iter_{\max}} * iter$$



PARTICLE SWARM OPTIMIZATION (PSO)

PSO Algorithm Flowchart



PARTICLE SWARM OPTIMIZATION (PSO)

Implementation of PSO for Solving OPF:

$$\begin{aligned} & Min \quad J(\mathbf{x},\mathbf{u}) \\ S.T. \quad & g(\mathbf{x},\mathbf{u}) = 0 \\ & h(\mathbf{x},\mathbf{u}) \le 0 \end{aligned}$$

Where:

$$\mathbf{x} = [P_{G1}, Q_G, V_L, S_{line}]$$

$$\mathbf{u} = [P_G, V_G, T, Q_c]$$

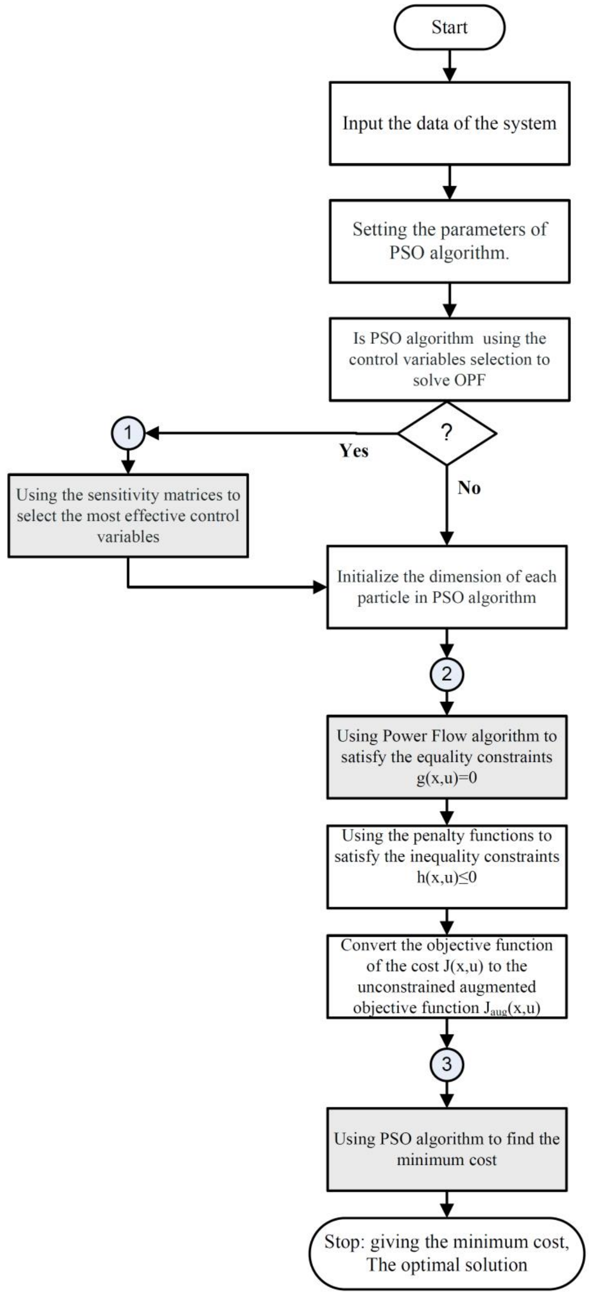
$$J_{aug} = J + \lambda_P (P_{G1} - P_{G1}^{\lim})^2 + \lambda_V \sum_{i=1}^{NL} (V_{Li} - V_{Li}^{\lim})^2 + \lambda_Q \sum_{i=1}^{NG} (Q_{Gi} - Q_{Gi}^{\lim})^2 + \lambda_S \sum_{i=1}^{nl} (S_{line,i} - S_{line,i}^{\max})^2$$

$$\Rightarrow J_{aug} = \sum_{i=1}^{NG} F_i(P_{Gi}) + \lambda \left[\sum_{i=1}^{NS} \mu_i * h(\mathbf{x},\mathbf{u}) \right]$$

Since: $$\mu_i = \begin{cases} 1; & h(\mathbf{x},\mathbf{u}) > 0 \\ 0; & h(\mathbf{x},\mathbf{u}) \le 0 \end{cases}$$

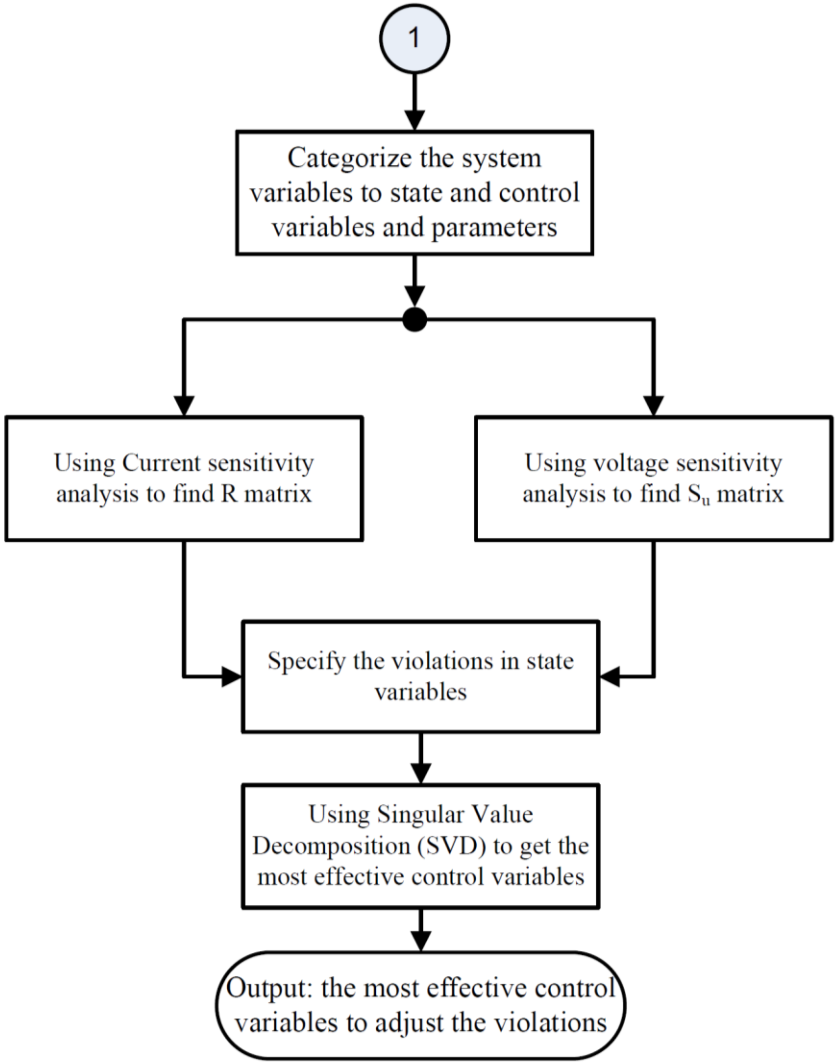
STUDY CASES AND SIMULATION RESULTS

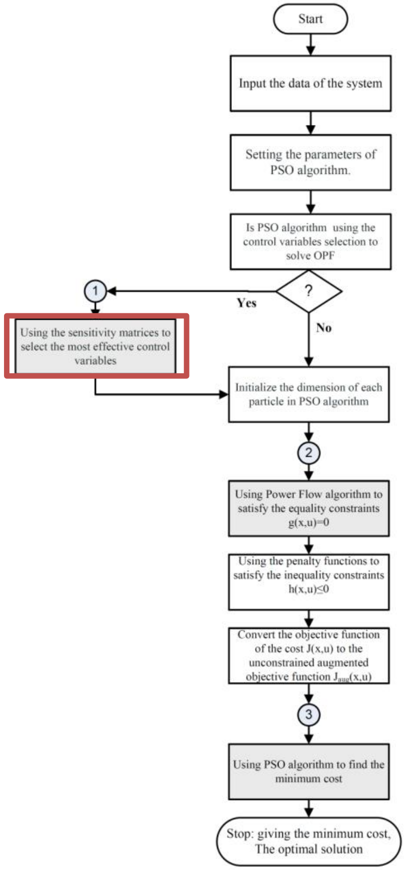
OPF Main Flowchart



STUDY CASES AND SIMULATION RESULTS

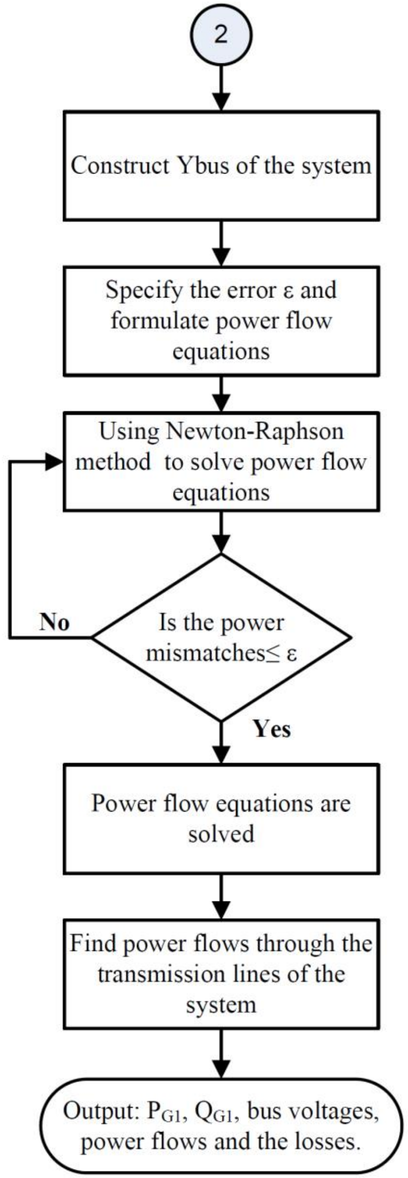
Using Sensitivity Matrices to Select the Most Control Variables:

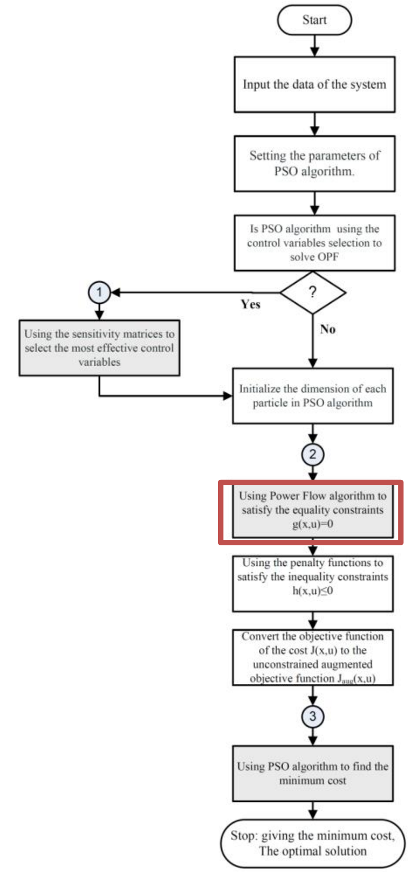




STUDY CASES AND SIMULATION RESULTS

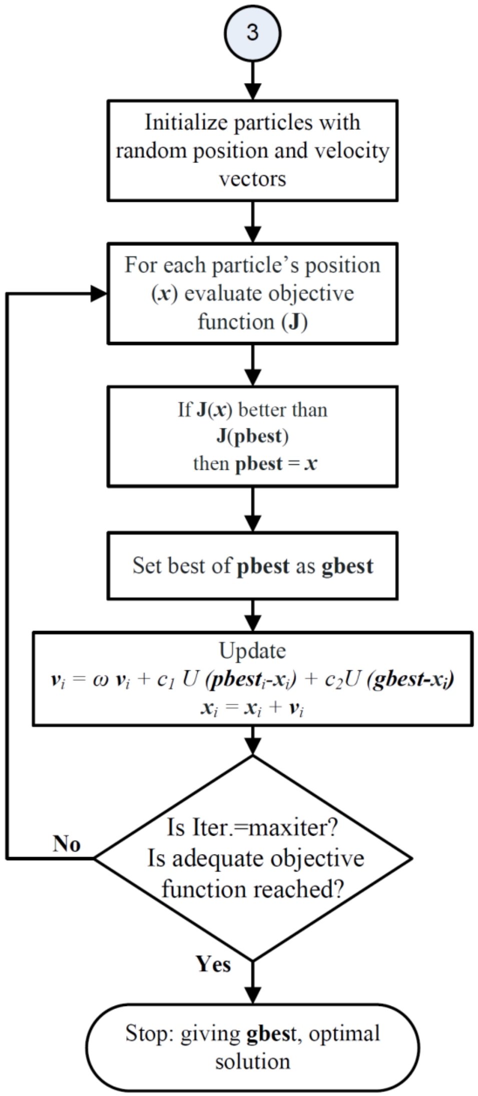
Using Power Flow algorithm to satisfy the equality constraints g(x,u)=0

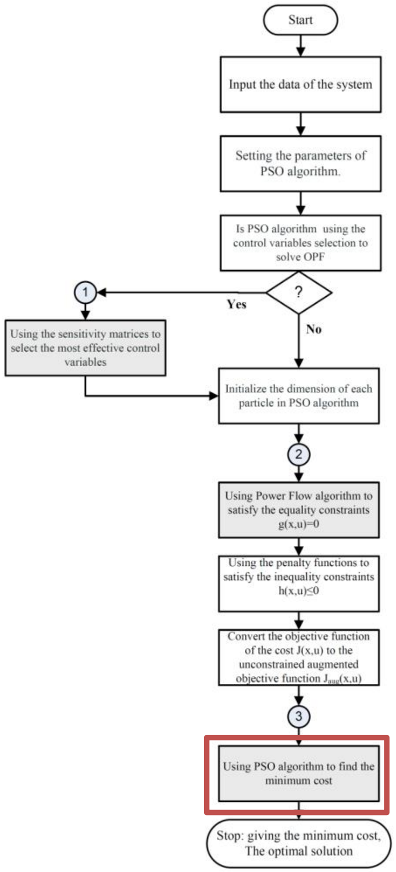




STUDY CASES AND SIMULATION RESULTS

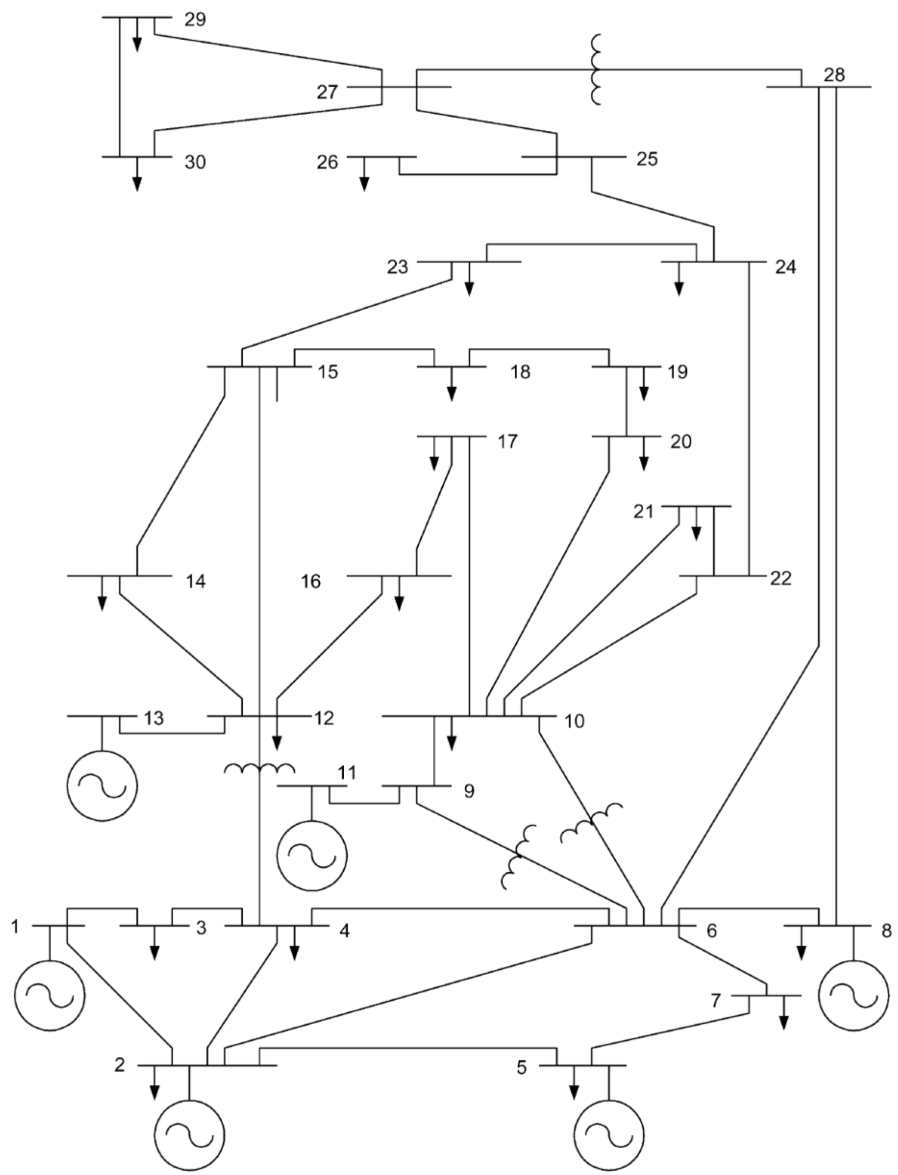
Using PSO algorithm to find the minimum cost





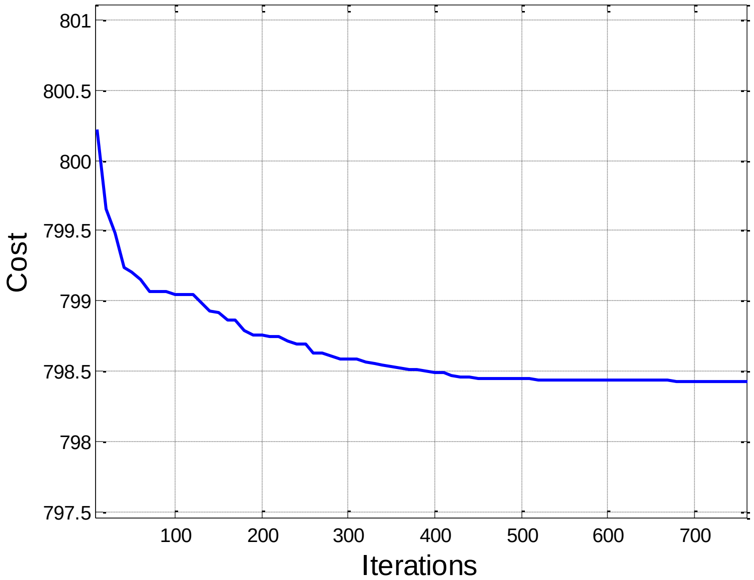
STUDY CASES AND SIMULATION RESULTS

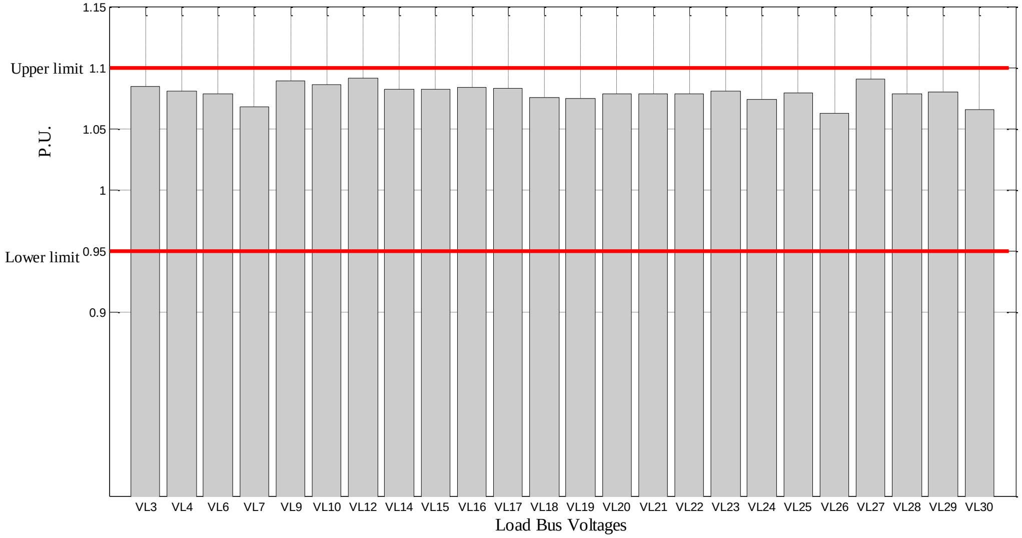
IEEE 30-BUS TEST SYSTEM:



STUDY CASES AND SIMULATION RESULTS

Study of Base Case:





P_{G1} (MW)	P_{G2} (MW)	P_{G3} (MW)	P_{G4} (MW)	P_{G5} (MW)	P_{G6} (MW)	Losses (MW)	Cost ($/hr)
176.94	48.71	21.27	21.09	11.83	12.00	8.4382	798.43

STUDY CASES AND SIMULATION RESULTS

Application of Sensitivity Analysis for OPF :

The order of most effective control variables is:

VL19	VL20	VL21	VL22	VL23	VL24	VL25	VL26	VL27	VL29	VL30
V8	T27	V2	T27	V1	V8	V1	V8	T27	V8	V8
V2	V5	V8	V1	V2	V5	V5	V2	V13	V1	V1
V1	V8	V1	V2	V8	V2	V2	V5	T12	V2	V2
V5	V2	V5	V5	V5	V1	V13	V1	Qsh23	V5	V5
V11	V1	T27	V8	T27	V11	T12	V13	Qsh29	V13	V13
T9	V11	V11	V13	Qsh29	T9	V8	T12	Qsh24	T12	T12
T27	T9	T9	T12	V11	T27	V11	T10	V1	Qsh23	V11
V13	V13	V13	V11	T9	T10	T9	V11	V2	V11	T9
T12	T12	T12	T9	V13	V13	T10	T9	V8	T9	T10
Qsh23	T10	Qsh29	Qsh29	T12	T12	Qsh20	Qsh15	V5	T10	Qsh15
Qsh29	Qsh29	Qsh23	Qsh23	T10	Qsh15	Qsh15	Qsh23	T10	Qsh15	T27
T10	Qsh24	T10	T10	Qsh20	Qsh17	T27	T27	Qsh15	T27	Qsh29
Qsh24	Qsh23	Qsh15	Qsh15	Qsh21	Qsh20	Qsh12	Qsh12	V11	Qsh24	Qsh12
Qsh12	Qsh17	Qsh12	Qsh12	Qsh17	Qsh29	Qsh17	Qsh17	T9	Qsh12	Qsh23
Qsh15	Qsh21	Qsh20	Qsh24	Qsh12	Qsh12	Qsh23	Qsh20	Qsh12	Qsh17	Qsh24
Qsh20	Qsh10	Qsh17	Qsh21	Qsh10	Qsh23	Qsh29	Qsh24	Qsh20	Qsh20	Qsh20
Qsh17	Qsh12	Qsh24	Qsh20	Qsh24	Qsh10	Qsh24	Qsh21	Qsh17	Qsh29	Qsh17
Qsh21	Qsh20	Qsh10	Qsh17	Qsh15	Qsh21	Qsh21	Qsh29	Qsh21	Qsh21	Qsh21
Qsh10	Qsh15	Qsh21	Qsh10	Qsh23	Qsh24	Qsh10	Qsh10	Qsh10	Qsh10	Qsh10

STUDY CASES AND SIMULATION RESULTS

Using combinations of the most effective control variables for Base Case OPF:

Case	Violation	Control variables	Still exist violations	Cost
283.4MW	*V_L18…30, S_{line1}	(**P_{gs}), (Vg1, Vg5, Vg8)	V_{L26}, V_{L30}, S_{line10}	818.92
283.4MW	V_L18…30, S_{line1}	(P_{gs}), (Vg1, Vg2, Vg8)	V_{L30}, S_{line10}	805.51
283.4MW	V_L18…30, S_{line1}	(P_{gs}), (Vg1, Vg2, Vg5, Vg8, Vg13)	V_{L30}	800.17
283.4MW	V_L18…30, S_{line1}	(P_{gs}), (Vg1, Vg2, Vg8), (T27)	-----	802.41
283.4MW	V_L18…30, S_{line1}	(P_{gs}), (Vgs)	-----	799.86
283.4MW	V_L18…30, S_{line1}	All (i.e. Pgs, Vgs, Ts, Qshs)	-----	798.43

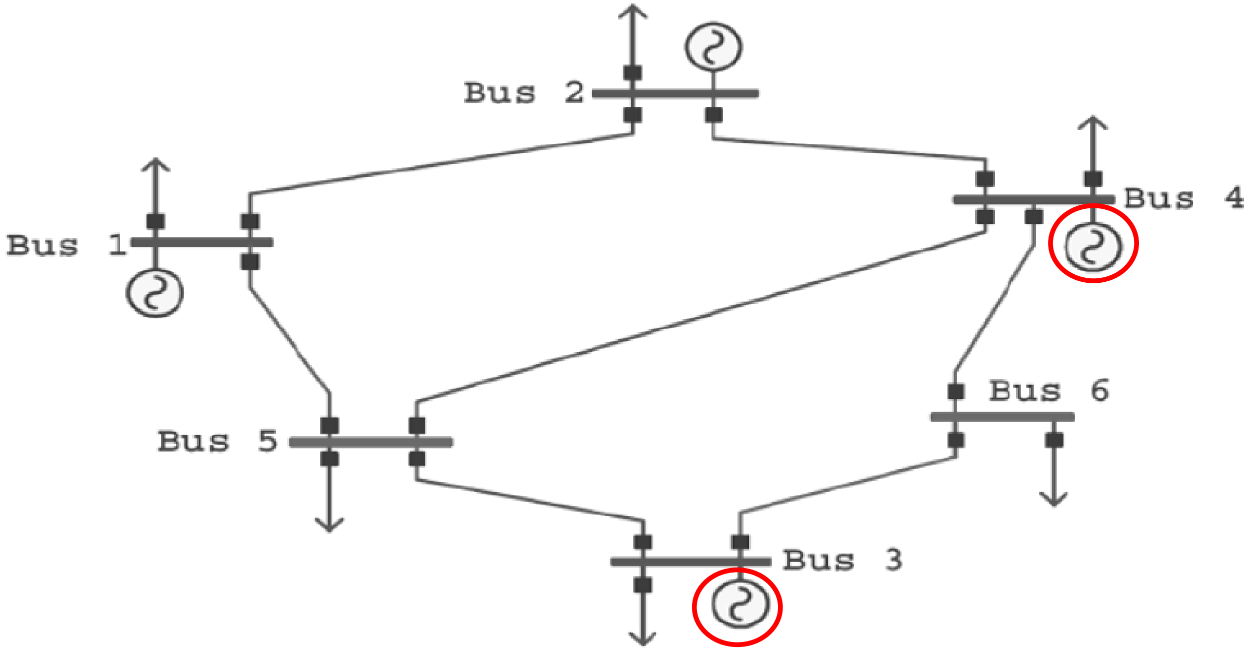
* V_L18…30 stands for violations at buses 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 29, 30.
** P_{gs} stands for all real power of generators except the first generator at slack bus.

The order of most effective control variables is:

VL19	VL20	VL21	VL22	VL23	VL24	VL25	VL26	VL27	VL29	VL30
V8	T27	V2	T27	V1	V8	V1	V8	T27	V8	V8
V2	V5	V8	V1	V2	V5	V5	V2	V13	V1	V1
V1	V8	V1	V2	V8	V2	V2	V5	T12	V2	V2
V5	V2	V5	V5	V5	V1	V13	V1	Qsh23	V5	V5
V11	V1	T27	V8	T27	V11	T12	V13	Qsh29	V13	V13
T9	V11	V11	V13	Qsh29	T9	V8	T12	Qsh24	T12	T12
T27	T9	T9	T12	V11	T27	V11	T10	V1	Qsh23	V11

STUDY CASES AND SIMULATION RESULTS

6-BUS SYSTEM INCLUDING WIND-POWERED GENERATORS



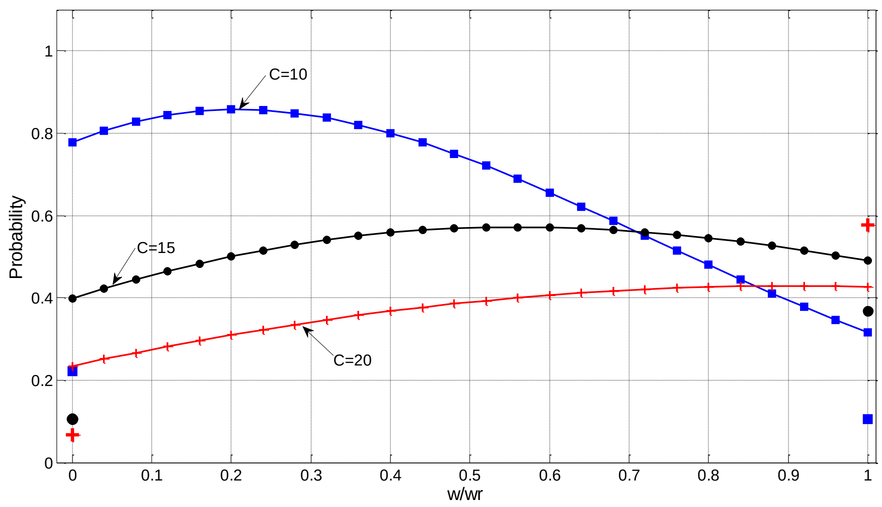
Gen. No.	a ($/MW^2.hr)	b ($/MW.hr)	c	PG_low (MW)	PG_high (MW)
1	0.012	12	105	50	250
2	0.0096	9.6	96	50	250
3	0	8	0	0	40
4	0	6	0	0	40

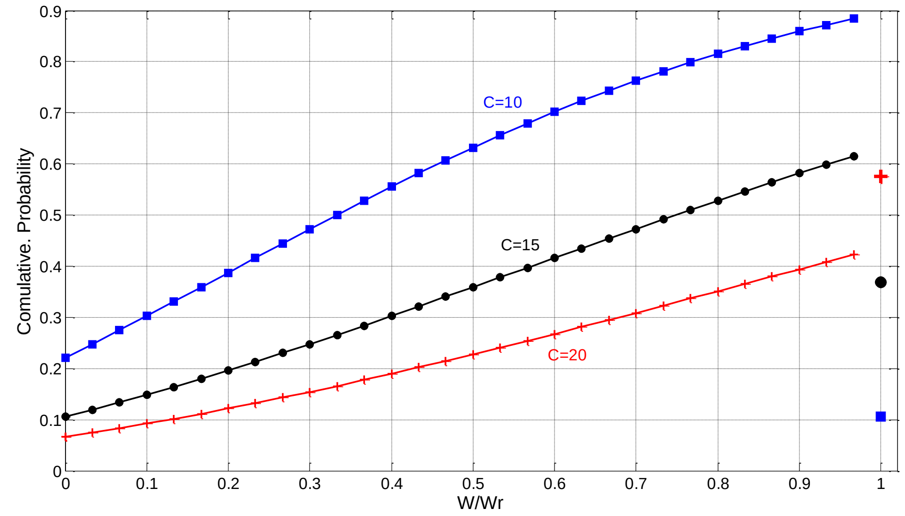
STUDY CASES AND SIMULATION RESULTS

6-BUS SYSTEM INCLUDING WIND-POWERED GENERATORS

$$Minimize: J = \sum_{i}^{M} C_i(p_i) + \sum_{i}^{N} C_{wi}(w_i) + \sum_{i}^{N} C_{p,i}(w_i) + \sum_{i}^{N} C_{r,i}(w_i)$$

$$f_W(w) = \frac{klv_i}{w_r c}\left(\frac{(1+\rho l)v_i}{c}\right)^{k-1} \exp\left(-\left(\frac{(1+\rho l)v_i}{c}\right)\right)^k$$

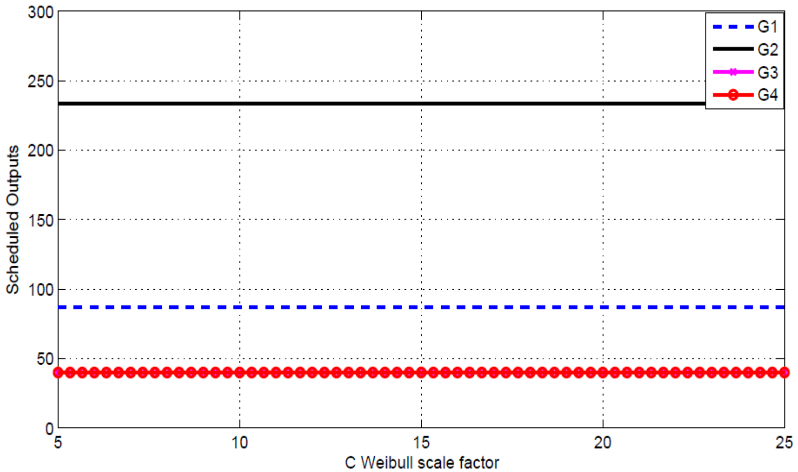




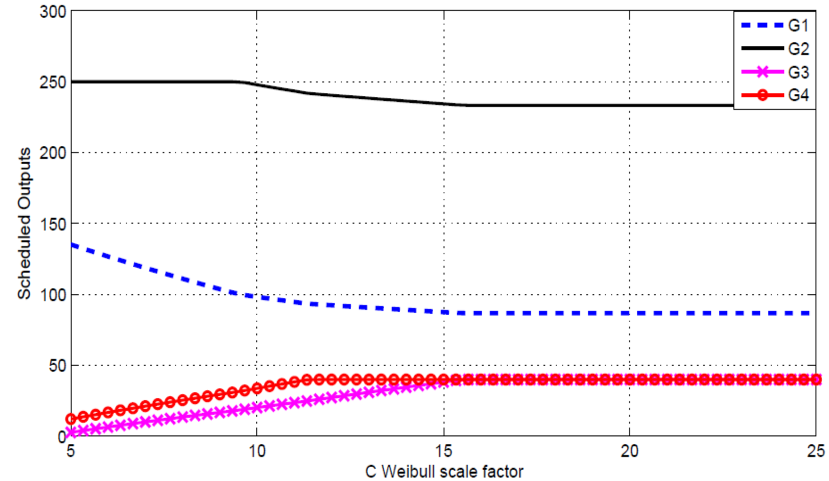
STUDY CASES AND SIMULATION RESULTS

The Effect of Wind Power Cost Coefficients

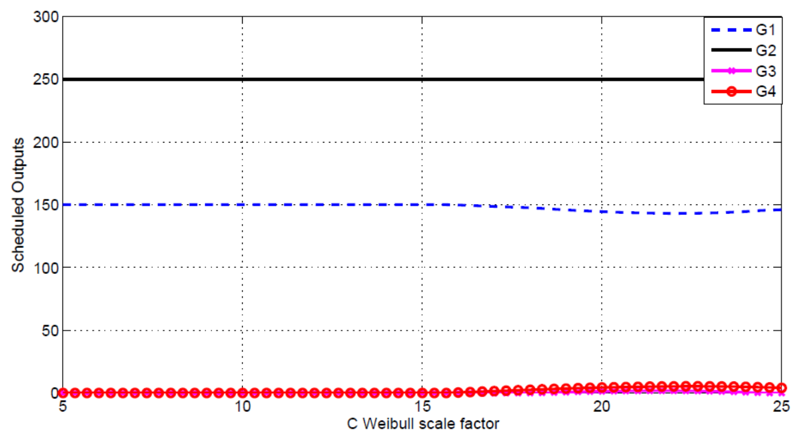
The Effects of Reserve Cost Coefficient k_r (and k_p=0):



(a) k_r=1



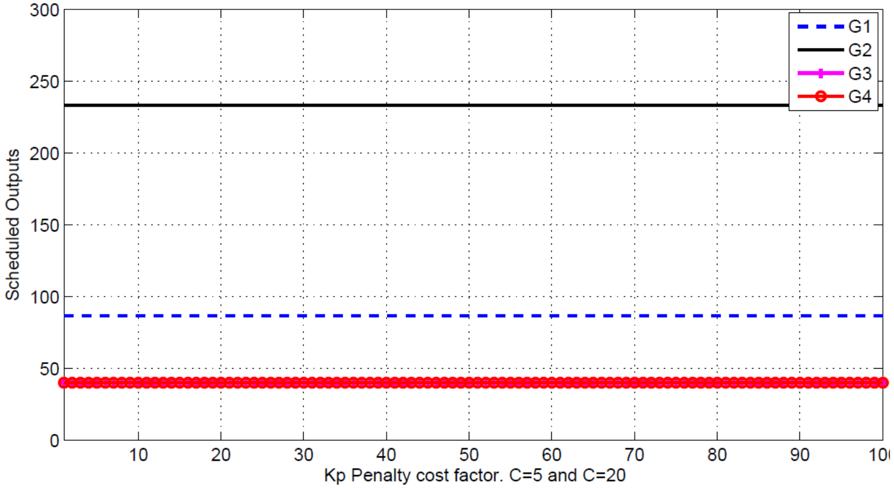
(b) k_r=10



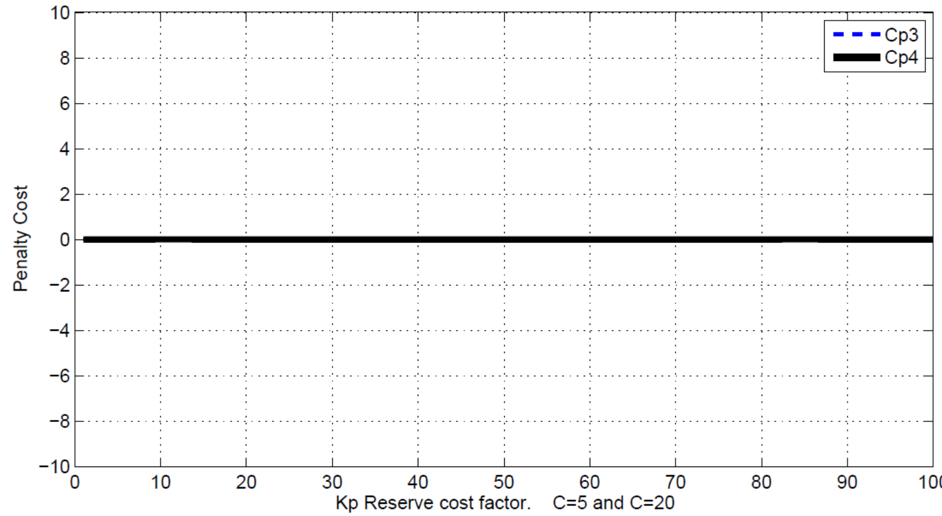
(c) k_r=100

STUDY CASES AND SIMULATION RESULTS

The Effects of Penalty Cost Coefficient k_p (and k_r=0):



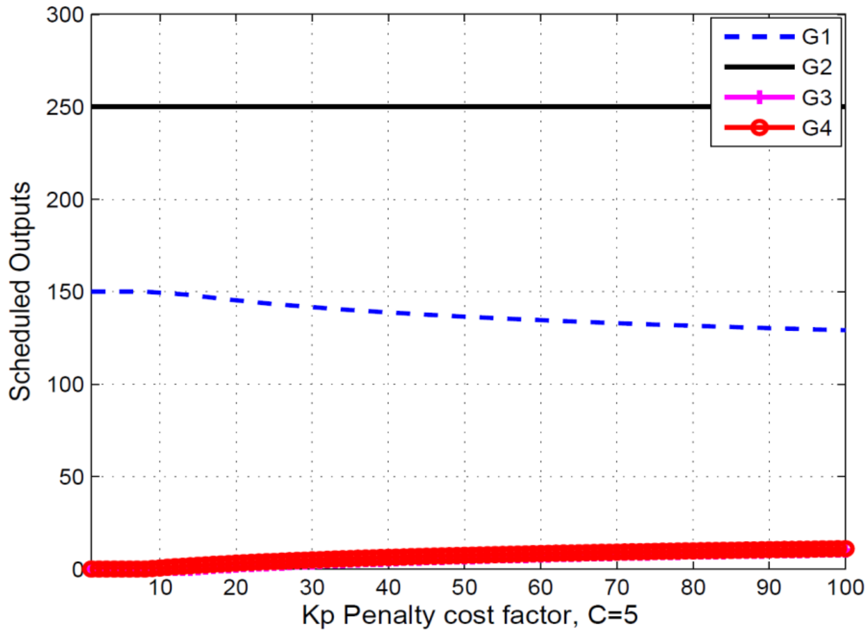
(a) Generators' Outputs



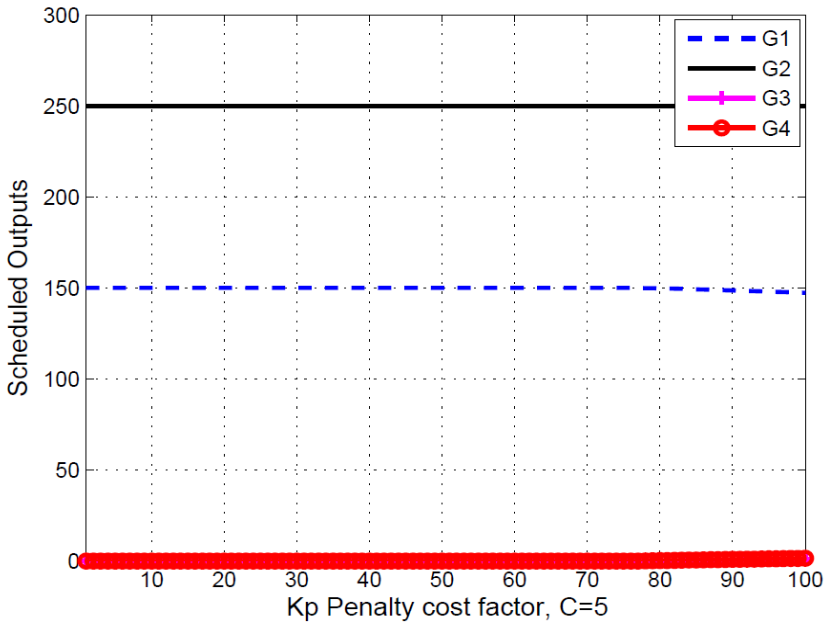
(b) Penalty Cost C_p

STUDY CASES AND SIMULATION RESULTS

The Effects of Reserve Cost Coefficient k_r and Penalty Cost Coefficient k_p:



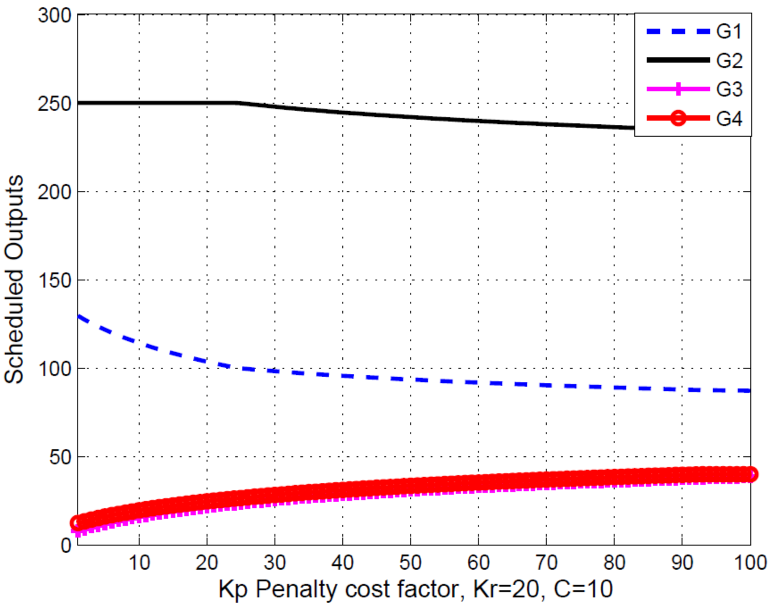
(a) k_r=20



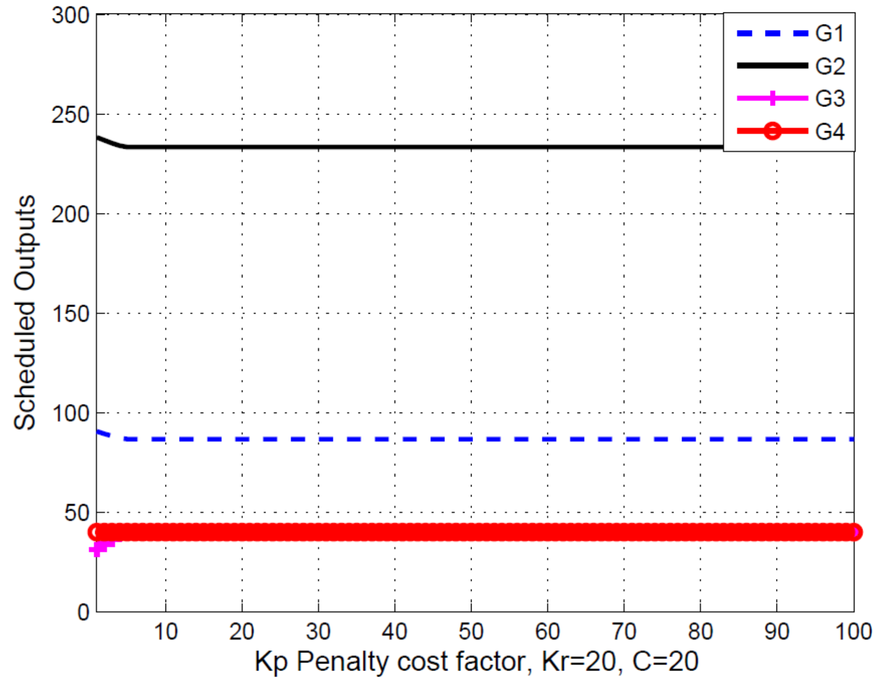
(b) $k_r = 60$

STUDY CASES AND SIMULATION RESULTS

The Effects of Reserve Cost Coefficient k_r and Penalty Cost Coefficient k_p:



(a) $c = 10$



(b) $c = 20$

Conclusion and Further Work

Conclusion

- The implementation of PSO algorithm to find OPF solution is useful and worth of investigation.

- PSO algorithm is easy to apply and simple since it has less number of parameters to deal with comparing to other modern optimization algorithms.

- PSO algorithm is proper for optimal dispatch of real power of generators that include wind-powered generators.

- The used model of real power optimal dispatch for systems that include wind power is contains possibilities of underestimation and overestimation of available wind power plus to whether the utility owns wind turbines or not; these are the main features of this model.

Conclusion and Further Work

Conclusion

- The probability manipulation of wind speed and wind power of the model is suitable since wind speed itself is hard of being expected and hence the wind power as well.

- In IEEE 30-bus test system, OPF has been achieved by using PSO and gives the minimum cost for several load cases.

- Using OPF sensitivity analysis can give an indication to which of control variables have most effect to adjust violations of operating constraints.

- The variations of wind speed parameters and their impacts on total cost investigated by 6-bus system.

Conclusion and Further Work

Further Work

- PSO algorithm needs some work on selecting its parameters and its convergence.

- PSO can be applied in wind power bid marketing between electric power operators.

- The same model can be adopted for larger power systems with wind power.

- The environment effects and security or risk of wind power penetration can be included in the proposed model and it becomes multi-objective model of optimal dispatch.

- Fuzzy logic is worth of investigation to be used instead probability concept which is used in the proposed model, especially when security of wind power penetration is included in the model.

Conclusion and Further Work

Further Work

- Using the most effective control variables to adjust violations in OPF needs more study.

- The incremental reserve and penalty costs of available wind power can be compared with incremental cost of conventional-thermal quadratic cost; this comparison could lead to useful simplifications of an economic dispatch model that includes thermal and wind power.

Thank You for Listening

Any Question
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