Electrical Power Quality and Utilisation, Journal Vol. XV, No. 1, 2009

Design and Analysis of Supercapacitors Energy Storage System for Energy Stabilization of Distribution Network

Kuldeep SAHAY and Bharti DWIVEDI

Uttar Pradesh Technical University,

***Summary*: Supercapacitors are the devices which can be store significant amounts of energy and quickly release it, their main application is for short term power compensation application where they can release a large amount of energy quickly and then can be recharged with smaller current. In this paper the use of supercapacitors bank is explored for energy stabilization and maintaining the voltage profile of the distribution system at the load point. The proposed supercapacitor bank is designed to improve the voltage profile of a distribution system by supplying the energy in case of demand and recharging the supercapacitors bank in valley period. The designed bank is of 50 kWh(180 MJ) of energy, 440 V voltages and peak power of 30 kW capacities for supply of energy in case of instantaneous need. The result shows that the SCESS can supply the instantaneous power for the back up the loads even though the voltage may drop up to 100 V; this SCESS can back up the load from 1.60-9.9974 hours depending upon the power demand while maintaining the minimum discharge voltage ratio and availability of useful energy**

Key words:
Power Distribution Network,
Supercapacitors Energy Storage
System (SCESS),
Energy Stabilization,
Back Up Time,
Equivalent Series Resistance (ESR) and Equivalent Parallel Resistance (EPR)

1. INTRODUCTION

Supercapacitor is a double layer capacitors, the energy is stored by charge transfer at the boundary between electrode and electrolyte. The amount of stored energy is a function of the available electrode and electrolyte. The amount of stored energy is a function of electrode surface, the size of the ions, and the level of the electrolyte decomposition voltage. Supercapacitors are constituted of two electrodes, a separator and an electrolyte. Two electrodes are made of activated carbon provides a high surface area part, defining the energy density. On the electrodes, current collectors with a high conducting part assure the interface between the electrodes and the connections of the supercapacitor. The two electrodes are separated by a membrane, which allows the mobility of charged ions and forbids electronic contact. The electrolyte supplies and conducts the ions from one electrode to the other.

The most important parameters of a supercapacitor include capacitance(C), ESR and EPR (which is also called leakage resistance) .Capacitance (C) decides the energy storage capability of super capacitor. Usually ESR is consists of electrode resistance, electrolyte resistance and contact resistance that wastes power for internal heating when charging or discharging in supercapacitors. ESR is almost less than one million but influences the energy efficiency and power density. EPR is an inner equivalent parallel resistance usually hundreds of kilo-ohms and decides the leakage current when the supercapacitor is in a stand by mode. ESR's is usually put forward to describe internal resistance when supercapacitor is estimated. The more layers separator has, the higher ESR therefore multilayer separator is not suitable for lower ESR. [1, 2, 3, 4, 5, 6, 7]

To obtain the higher voltages and proper energy storage capacity, it is necessary to connect supercapacitors in series and parallel combination. The huge energy stored in the supercapacitors is unable to distribute to a load due to its large equivalent series resistance, peak power is mainly limited by joule losses in the equivalent series resistance of the supercapacitors. When it is applied to large power density discharge, dynamic equivalent series resistance and ultimate discharge ability of supercapacitors is the dominating factor. The high capacitance permits the storage of large amounts of energy which leads to a large number of new applications. [8, 9, 10]

The voltage across a supercapacitor is given by:

$$U_C = Q/C \tag{1}$$

Where Q is the charge stored in a supercapacitors and C is capacitance of supercapacitors.

The energy stored is:

$$E = \frac{1}{2} C U_C^2 \tag{2}$$

When the super capacitor is discharged its voltage decreases; therefore the conditioning is required to maintain the output voltage and/or current of supercapacitor. Further some of available supercapacitor in market is shown in Table 1 and cost trend is also shown in Table 2.

2. MODELING & DESIGNING OF SUPERCAPACITORS BANK

2.1. Sizing of the Supercapacitor bank

The maximum energy stored in the supercapacitor bank depends on its equivalent capacitance C_{eq}. The expression for maximum energy storage can be represented as following:

$$E_{max} = \left(C_{eq} \times U_{max}^2\right) / 2 \tag{3}$$

Table.1 Available Supercapacitors in Market [11, 12, 13, 14, 15]

Sl.No.	Manufacturer	Specifications of Supercapacitors
1	Power Star China Make (single Unit)	50 F/2.7V, 300F/2.7V, 600F/2.7 V, ESR less than 1mΩ.
2	Panasonic Make (Single Unit)	0.022-70F,2.1-5.5V, ESR 200 mΩ-350 Ω
3	Maxwell Make (Module)	63F/125V,150A ESR 18 mΩ 94F/75 V,50 A,ESR 15 mΩ
4	Vinatech Make	10-600F/2.3V,ESR 400 -20 mΩ, 3-350F/2.7,ESR 90-8 mΩ
5	Nesscap Make (module)	15V/33F , ESR 27 mΩ 340V/ 51F, ESR 19 mΩ

Table 2. Supercapacitor Cost Trend [16]

Sl.No.	Year	Cost /Farad ($)	Cost/kJ($)
1	1996	0.75	281.55
2	1998	0.40	151.23
3	2000	0.01	32
4	2002	0.023	7.51
5	2006	0.010	2.85
6	2010	0.005	1.28

Where:

E_{max} — is the maximum energy storage capacity.

C_{eq} — is equivalent capacitance of supercapacitor bank in Farad.

U_{max} — is maximum voltage of the supercapacitor bank.

Practically it is not feasible to allow the supercapacitor bank to discharge all this energy therefore minimum allowable voltage limit is fixed that limits available energy. The discharge voltage ratio for the supercapacitor bank is represented as following:

$$\%d = U_{min} / U_{max} \times 100 \tag{4}$$

Where:

$\%d$ — is percentage discharge ratio.

U_{min} — is minimum allowable voltage limit.

U_{max} — is maximum voltage of the supercapacitor bank.

The Depth of Discharge can be expressed as following:

$$DOD = (100 - d) = 100\left(1 - \frac{U_{min}}{U_{max}}\right) \tag{5}$$

DOD is measure of how much energy has been withdrawn from a storage device, expressed as a percentage of full capacity. For example, 100Ah battery from which 30Ah has been withdrawn has undergone 30% depth of discharge (DOD). Depth of discharge is inverse of state of charge (SOC); the example would be at 70% SOC.

In power controlled operation mode it is necessary to maintain the minimum voltage so the a required power can be discharged, therefore minimum discharge voltage can be represented by following expression

$$U_{min} = R_{eq} I_D = \sqrt{(R_{eq} P_D)} \tag{6}$$

Where:

U_{min} — is minimum discharge voltage permitted in volt.

R_{eq} — is equivalent series resistance of supercapacitor bank in ohm.

I_D — is discharge current in amp.

P_D — is discharge power in kW.

$$I_D = \sqrt{\frac{P_D}{R_{eq}}} \tag{7}$$

Where:

R_{eq} — is equivalent series resistance of supercapacitor bank in ohm.

I_D — is discharge current in amp.

P_D — is discharge power in kW.

Now the percentage discharge voltage ratio can be expressed using equation no. (7)

$$\%d_{min} = 100\sqrt{R_{eq} P_D} / U_{max} \tag{8}$$

Where:

d_{min} — is minimum discharge voltage ratio.

R_{eq} — is equivalent series resistance of supercapacitor bank in ohm.

P_D — is discharge power in kW.

U_{max} — is maximum voltage of supercapacitor bank in volt.

The maximum power that can be withdrawn from the supercapacitor bank can be expressed as following as per maximum power transfer theorem:

$$P_{D max} = U_{max}^2 / 4R_{eq} \tag{9}$$

Where:

P_{Dmax} — is maximum dischargeable power.

U_{max} — is maximum voltage of supercapacitor bank.

R_{eq} — is equivalent series resistance of supercapacitor bank in ohm.

Once the voltage constraints have been obtained i.e. $U_{min} < U < U_{max}$ then the useful energy that the supercapacitor bank can provide can be expressed as following:

$$E_u = C_{eq}\left(U_{max} - U_{min}\right)^2 / 2 \qquad (10)$$

Dividing equation (12) by equation (6):

$$\frac{E_u}{E_{max}} = \frac{\left(U_{max} - U_{min}\right)^2}{U_{max}^2} \qquad (11)$$

$$\frac{E_u}{E_{max}} = \left(1 - {U_{min}}\big/{U_{max}}\right)^2 \qquad (12)$$

Expanding equation no. (12) and neglecting other terms then the expression would be:

$$\frac{E_u}{E_{max}} = \left[\left(1 - {U_{min}}\big/{U_{max}}\right)^2\right] \qquad (13)$$

Above can be expressed in term of depth of discharge:

$$E_u = E_{max}\left[1 - \left(d/100\right)^2\right] \qquad (14)$$

Therefore the total capacitance of supercapacitor bank can be expressed in term of useful energy and maximum voltage:

$$C_{Teq} = 2\frac{E_u}{U_{max}^2\left[1 - \left(d/100\right)^2\right]} \qquad (15)$$

Here it is important to consider the efficiency of the supercapacitor bank which would finally decide the number of cells to be connected in series to obtain the maximum voltage of the bank and energy storage capacity of the bank.

Let the storage efficiency of the supercapacitor bank η_s:

$$C_{eq} = 2\frac{E_u}{\eta_s U_{max}^2\left[1 - \left(d/100\right)^2\right]} \qquad (16)$$

2.2. Equivalent Capacitance of Supercapacitor bank

The capacitance (C) is the most important parameters of a supercapacitor, though the supercapacitor can work at high voltage without connecting many cells in series but to interface the higher voltages and proper energy storage capacity, it is necessary to connect supercapacitors in series and parallel combination. The high capacitance permits the storage of large amounts of energy which leads to a large number of new applications like bulk electricity price arbitrage, transmission congestion relief, distribution upgrade deferral, transmission upgrade deferral, availability based use, renewable capacity firming and etc.

In general, the number of series connected cells N_s in one branch are imposed by the rating of supercapacitor cells maximum voltage available in the market or in the stack.

$$N_s = U_{max} / U_{cell} \qquad (17)$$

Where:

N_s — are number of cell connected in series.

U_{max} — is maximum voltage of the supercapacitor bank.

U_{cell} — is rating of supercapacitor cell.

The number of parallel branch N_p in the supercapacitor bank can be found by:

$$N_p = N_s C_{eq} / C_{cell} \qquad (18)$$

To have sufficient energy storage capacity number of parallel branches must be more than or equal to the one ($N_p \geq 1$) and rounded upward side to nearest integer.

The equivalent capacitance of the supercapacitor bank is represented by the following formula:

$$C_{eq} = \left(N_p \times C_{cell}\right)/ N_s \qquad (19)$$

Where:

C_{eq} — is equivalent capacitance of supercapacitor bank in Farad.

C_{cell} — is capacitance of each cell in Farad.

N_s — are number of cell connected in series.

N_p — is number of parallel arms in supercapacitor bank.

From equation (19) it is clear that to have net higher equivalent capacitance of the bank, number of the parallel arms (N_p) should be always higher than N_s thereby higher energy storage capacity.

Total numbers of cell in Supercapacitor bank would be:

$$N_T = N_s \times N_p \qquad (20)$$

Where:

N_T — is total number of cells required in supercapacitor bank.

N_s — are number of cell connected in series.

N_p — is number of parallel arms in supercapacitor bank.

2.3. Equivalent Series Resistance of Supercapacitor bank

ESR is consists of electrode resistance, electrolyte resistance and contact resistance that wastes power causes internal heating when charging or discharging in Supercapacitor. ESR is almost less than one million but influences the energy efficiency and power density. While designing the supercapacitor energy storage bank numbers of supercapacitor cells are connected in series and parallel thereby total series resistance of bank increases, called equivalent series resistance of the bank, which is represented by following formula:

$$R_{eq} = \left(R_s \times N_s\right)/ N_p \qquad (21)$$

Where:

R_{eq} — is equivalent series resistance of supercapacitor bank in ohm.

R_s — is series resistance of each cell in ohm.
N_s — is number of cell connected in series.
N_p — is number of parallel arms in supercapaciton bank.

From equation (21) it is clear that to have net lower equivalent series resistance of the bank, number of the parallel arms should always higher than N_s thereby lower ohmic losses in the supercapacitor bank while charging and discharging. [17, 18, 19, 20]

2.4. Analysis of Supercapacitor Bank Charging Efficiency

The equivalent representation of supercapacitor bank would be by in series with equivalent resistance, the bank would be charged at constant power (power controlled mode).

Where:

U_{sc} — is the voltage across the supercapacitor bank.
P_c — is constant power at which charging of supercapacitor bank would take place.

Then the expression for charging current can be expressed as:

$$i_c = C_{eq} \cdot \frac{dU}{dt} = \frac{P_c}{U_{sc}} \tag{22}$$

V — is voltage across the equivalent capacitance of the supercapacitor bank can be expressed using KVL

$$U = U_{sc} - R_{eq} \cdot \frac{P_c}{U_{sc}} \tag{23}$$

Differentiating the equation 23 with respect to V_{sc} can be expressed as:

$$\frac{dU}{dU_{sc}} = 1 + \frac{R_{eq} \cdot P_c}{U_{sc}^2}$$

or: (24)

$$dU = \left(1 + \frac{R_{eq} \cdot P_c}{U_{sc}^2}\right) dU_{sc}$$

The equation (22) can be also be expressed as following:

$$dU = \frac{P_c}{U_{sc}} \cdot \frac{dt}{C_{eq}} \tag{25}$$

After equating equation 24 & 25 it can be represented as:

$$\frac{P_c}{U_{sc}} \cdot \frac{dt}{C_{eq}} = \left(1 + \frac{R_{eq} \cdot P_c}{U_{sc}^2}\right) dU_{sc}$$

or: (26)

$$P_c dt = C_{eq} U_{sc} \left(1 + \frac{R_{eq} \cdot P_c}{U_{sc}^2}\right) dU_{sc}$$

Integrating equation 26 from minimum voltage U_{min} to maximum voltage U_{max} within the charge time T_c would give the charge energy W_c expressed:

$$W_c = \int_0^{T_c} P_c dt = \int_{U_{min}}^{U_{max}} C_{eq} U_{sc} \left(1 + \frac{R_{eq} \cdot P_c}{U_{sc}^2}\right) dU_{sc}$$

or: (27)

$$W_c = P_c T_c = \frac{C_{eq} U_{max}}{2} \left(1 - d^2\right) - C_{eq} R_{eq} P_c \log(d)$$

It is to noted that d is the discharge voltage ratio defined such that $U_{min} = (1\text{-DOD}) U_{max}$ with the constraint $0 \le d \le 1$.

The effective energy W_e that can be stored in the super capacitor's bank equivalent capacitance C_{eq} be obtained as integrating for charging time T_c while fulfilling the minimum voltage criteria i.e. U_{min} to U_{max}, since there would be voltage drop across the equivalent resistance R_{eq} of bank. Therefore the expression can be shown as:

$$W_e = \int_0^{T_c} U i_c dt = \int_{min}^{max} U C_{eq} dU \tag{28}$$

In the above equation putting the value of U and dU from the equation numbers 23 and 24 then above can be expressed as:

$$W_e = \int_{min}^{max} C_{eq} \left(U_{sc} - R_{eq} \cdot \frac{P_c}{U_{sc}}\right)\left(1 + \frac{R_{eq} \cdot P_c}{U_{sc}^2}\right) dU_{sc} \tag{29}$$

After integrating the above equation can be expressed in term of discharge voltage ratio d:

$$W_e = \frac{C_{eq} U_{max}^2 \left(1 - d^2\right)}{2} \left[1 - \frac{R_{eq}^2 \cdot P_c^2}{d^2 \cdot U_{max}^2}\right] \tag{30}$$

The charging efficiency 'η_c' can be defined as ratio of effective energy 'W_e' stored to the charge energy 'W_c' at constant power mode P_c in the charge process, the expression can be written as following:

$$\eta_c = \frac{W_e}{W_c} = \frac{\dfrac{C_{eq} U_{max}^2 \left(1 - d^2\right)}{2} \left[1 - \dfrac{R_{eq}^2 \cdot P_c^2}{d^2 \cdot U_{max}^2}\right]}{\dfrac{C_{eq} U_{max}^2}{2} \left(1 - d^2\right) - C_{eq} R_{eq} P_c \log(d)}$$

or: (31)

$$\eta_c = \left[1 - \frac{R_{eq}^2 \cdot P_c^2}{d^2 \cdot U_{max}^2}\right] \left[1 - \frac{2 R_{eq} C_{eq} P_c \log(d)}{\left(1 - d^2\right) C_{eq} U_{max}^2}\right]^{-1}$$

2.5. Discharging Efficiency of Supercapacitor Bank

The equivalent representation of supercapacitor bank would be equivalent capacitance in series with equivalent resistance; the bank would be discharged at constant power (power controlled mode) as per requirement of the load.

Where:

U_{sc} — is the voltage across the supercapacitor bank.

P_d — is constant power at which discharging of supercapacitor bank would take place.

Then the expression for charging current can be expressed as:

$$i_d = C_{eq}\frac{dU}{dt} = \frac{P_d}{U_{sc}} \tag{32}$$

V is voltage across the equivalent capacitance of the supercapacitor bank can be expressed using KVL:

$$U = U_{sc} + R_{eq}\cdot\frac{P_d}{U_{sc}} \tag{33}$$

Differentiating the equation 23 with respect to V_{sc} can be expressed as:

$$\frac{dU}{dU_{sc}} = 1 - \frac{R_{eq}\cdot P_d}{U_{sc}^2}$$

or: (34)

$$dU = \left(1 - \frac{R_{eq}\cdot P_d}{U_{sc}^2}\right)dU_{sc}$$

The equation (32) can be also be expressed as following:

$$dU = \frac{P_d}{U_{sc}}\cdot\frac{dt}{C_{eq}} \tag{35}$$

After equating equation 34 & 35 it can be represented as:

$$\frac{P_d}{U_{sc}}\cdot\frac{dt}{C_{eq}} = \left(1 - \frac{R_{eq}\cdot P_d}{U_{sc}^2}\right)dU_{sc}$$

or: (36)

$$P_d dt = C_{eq}U_{sc}\left(1 - \frac{R_{eq}\cdot P_d}{U_{sc}^2}\right)dU_{sc}$$

Integrating equation (36) from minimum voltage U_{min} to maximum voltage U_{max} within the discharge time T_d would give the discharge energy W_d expressed:

$$W_d = \int_0^{dt} P_d dt = \int_{min}^{max} C_{eq}U_{sc}\left(1 - \frac{R_{eq}\cdot P_d}{U_{sc}^2}\right)dU_{sc}$$

or: (37)

$$W_d = P_d T_d = \frac{C_{eq}\cdot U_{max}^2}{2}\left(1 - d^2\right) + C_{eq}R_{eq}P_d \log(d)$$

It is to noted that d is the discharge voltage ratio defined such that U_{min}= (1-DOD)U_{max} with the constraint $0 \le d \le 1$, for particular discharge time.

Theoretically available energy W_{td} that can be stored in the super capacitor's bank equivalent capacitance C_{eq} can be obtained as integrating for discharging time T_d while fulfilling the minimum voltage criteria i.e. U_{min} to U_{max}, since there would be voltage drop across the equivalent resistance R_{eq} of bank. Therefore the expression can be shown as:

$$W_{td} = \frac{\left(1 - d^2\right)C_{eq}\cdot U_{max}^2}{2} \tag{38}$$

The discharging efficiency 'η_d' can be defined as ratio of discharge energy 'W_d' stored to the theoretically discharge energy 'W_{td}' at constant power mode P_d in the discharge process, the expression can be written as following:

$$\eta_d = \frac{W_d}{W_{td}} = \frac{\frac{C_{eq}\cdot U_{max}^2}{2}\left(1 - d^2\right) + C_{eq}R_{eq}P_d \log(d)}{\frac{\left(1 - d^2\right)C_{eq}\cdot U_{max}^2}{2}}$$

or: (39)

$$\eta_d = \frac{W_d}{W_{td}} = \left(1 + \frac{R_{eq}P_d \log(d)}{\left(1 - d^2\right)\cdot U_{max}^2}\right)$$

3. DESIGN & ANALYSIS OF SUPERCAPACITOR ENERGY STORAGE SYSTEM

The load on the distribution system varies time to time; further if there is deficit of energy or power in the peak hours the problem aggravates and the supply voltage profile drops then without increasing the generation capacity the system can be stabilize with the help of the supercapacitors energy storage system. The proposed supercapacitors energy storage system is designed to have storage 50 kWh (180 MJ) of energy, 440 V voltages and peak power of 30 kW to work when no supply is available to the consumers as well as there is voltage sag.

The following data have been considered while designing the supercapacitor bank in power controlled mode fulfilling the minimum discharge voltage ratio criteria. The supercapacitors used are of Maxwell Technology make having product specifications, Nominal capacitance 63 F, Rated voltage 125 V,ESR 18 mΩ ,Operating temperature range -40°C to +65°C, P_{max} 4,700W/kg, E_{max} 2.53Wh/kg ,Cycles 1,00,000, Lifespan 1,00,000 hours, Maximum continuous current 150 A, Maximum peak current(1 sec) 750 A, Leakage current 5.2 mA . In the Figures 1, 2, 3, 4, 5, 6,7,8,9 and 10 curves are shown below for performance analysis using the MATLAB.

In table-3 analysis of supercapacitor energy storage system has been given which have been obtained using MATLAB.

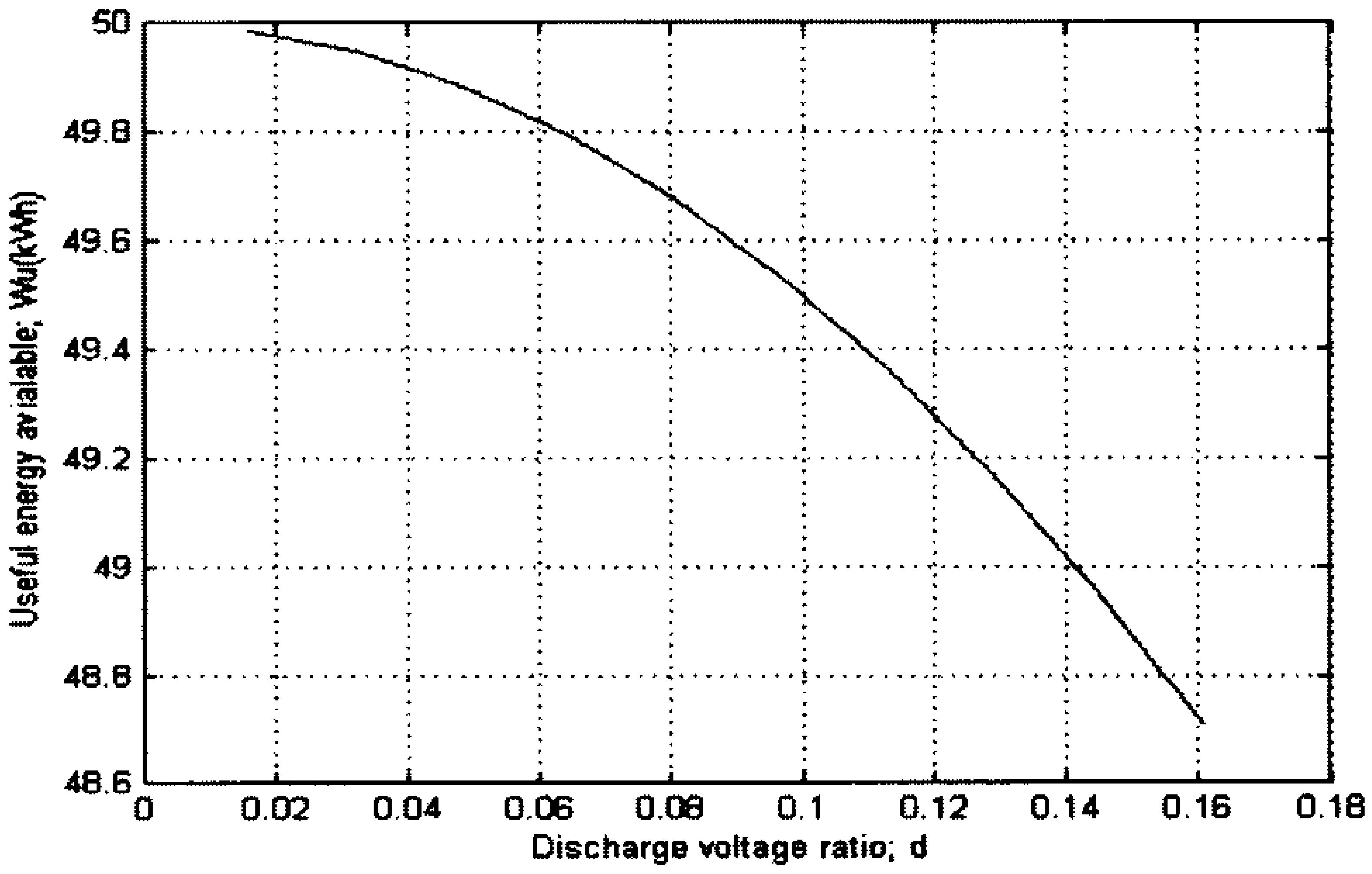


Fig. 1. Plot of Useful Energy with Discharge Voltage Ratio

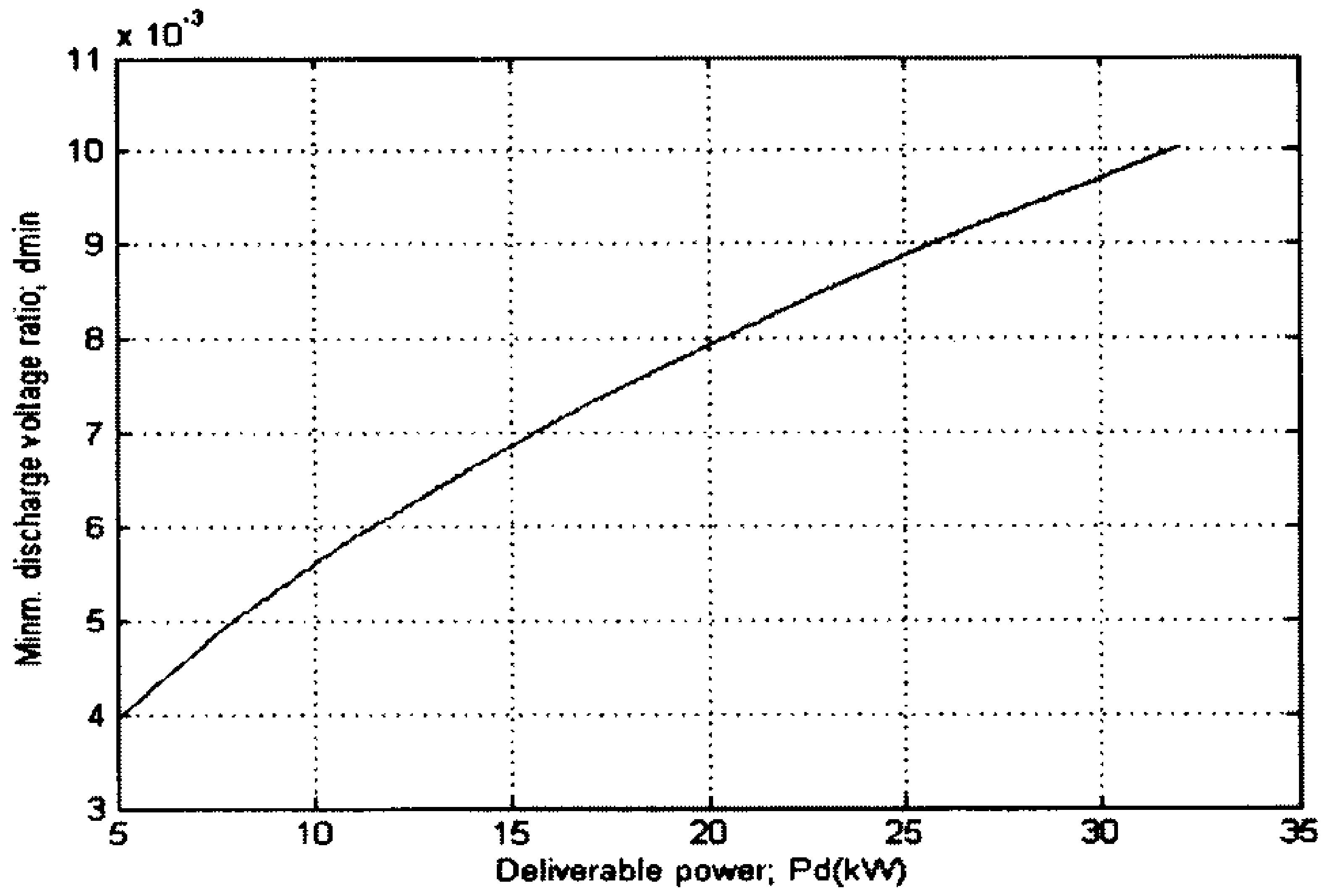


Fig. 2. Plot of deliverable Power Versus Minimum Discharge Voltage Ratio

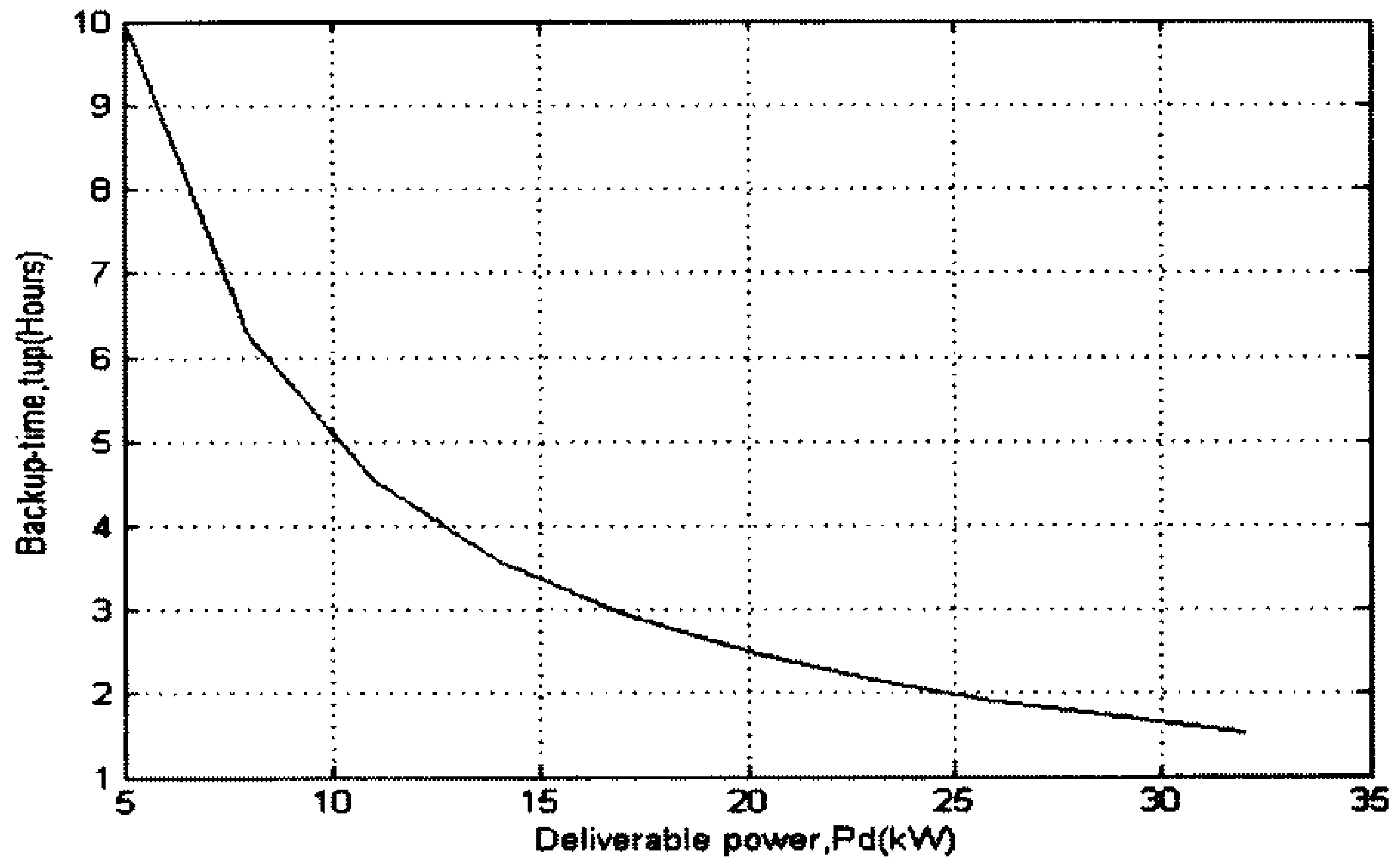


Fig. 3. Plot of Deliverable Power versus Backup-time

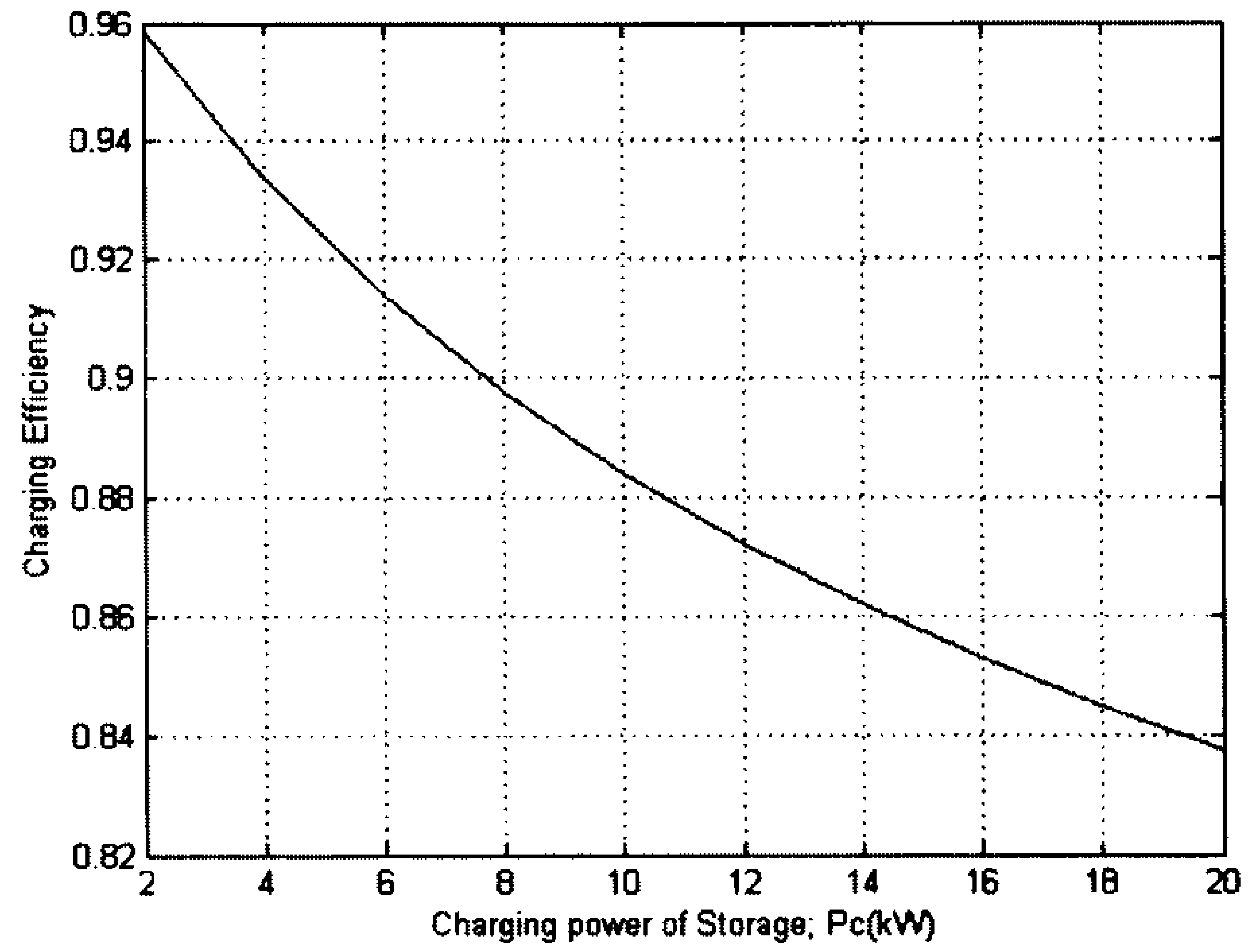


Fig. 4. Plot of Charging Power of Storage versus Charging Efficiency

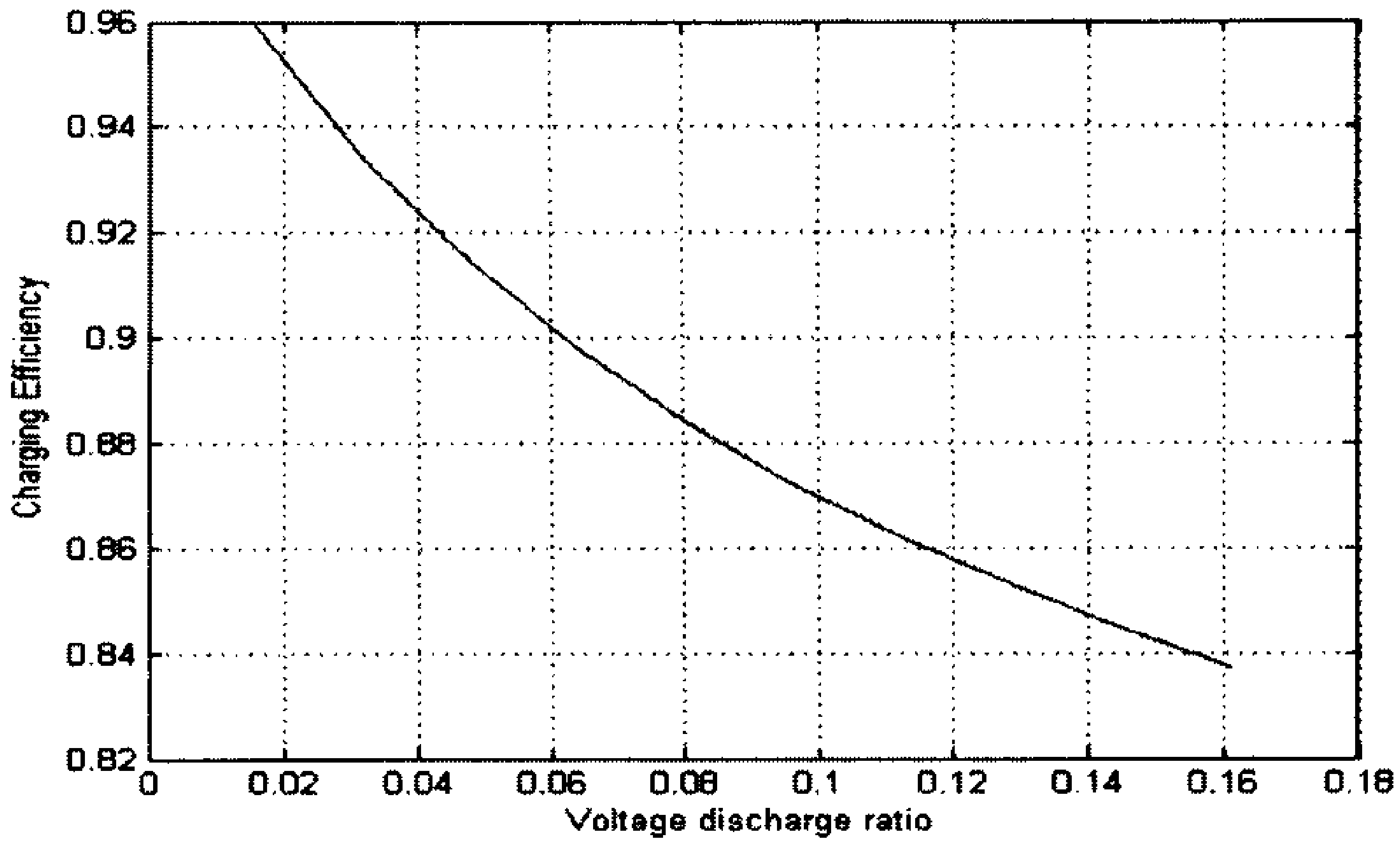


Fig. 5. Plot of Voltage discharge ratio versus Charging Efficiency

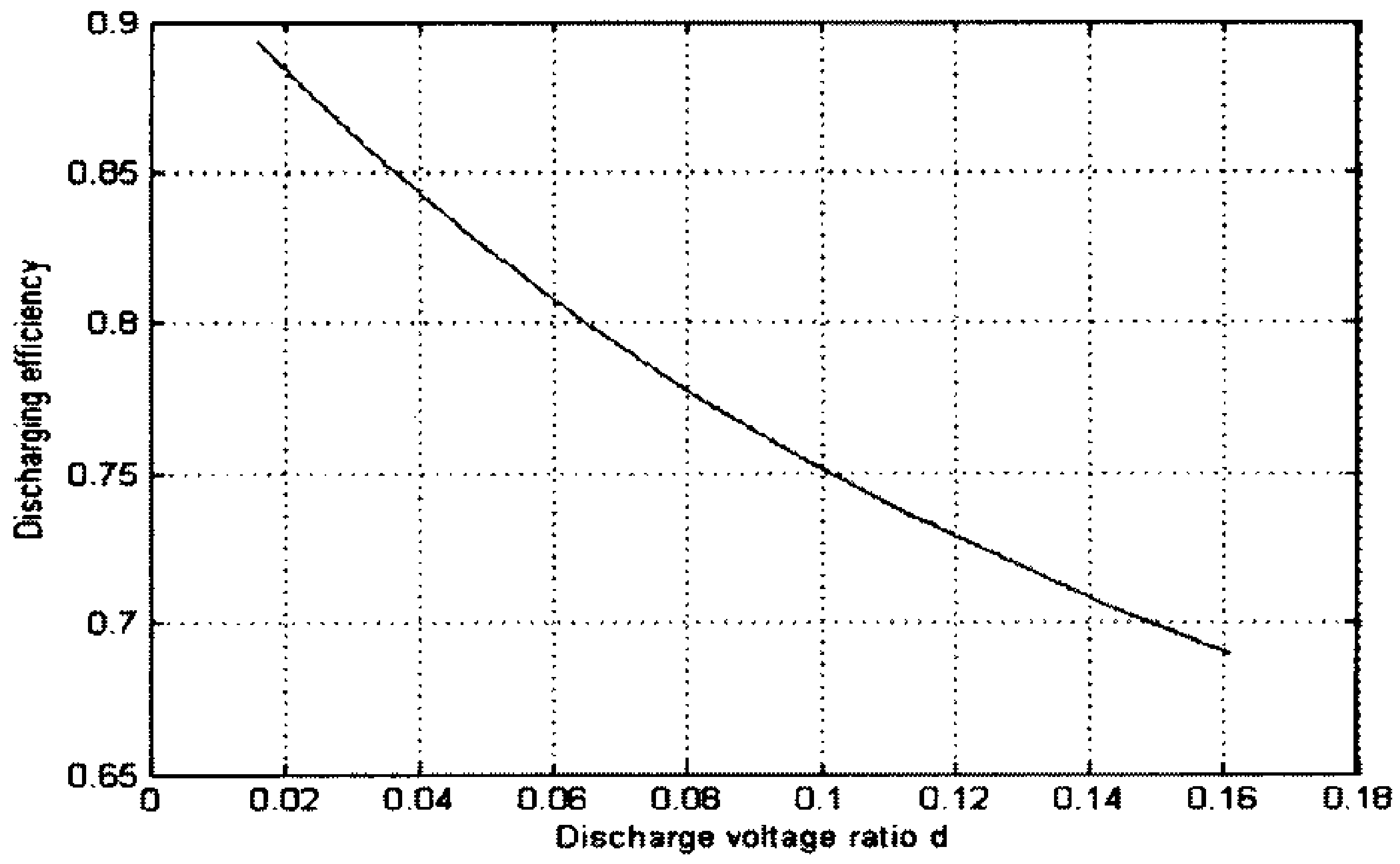


Fig. 6. Plot of Voltage discharge ratio versus Discharging Efficiency

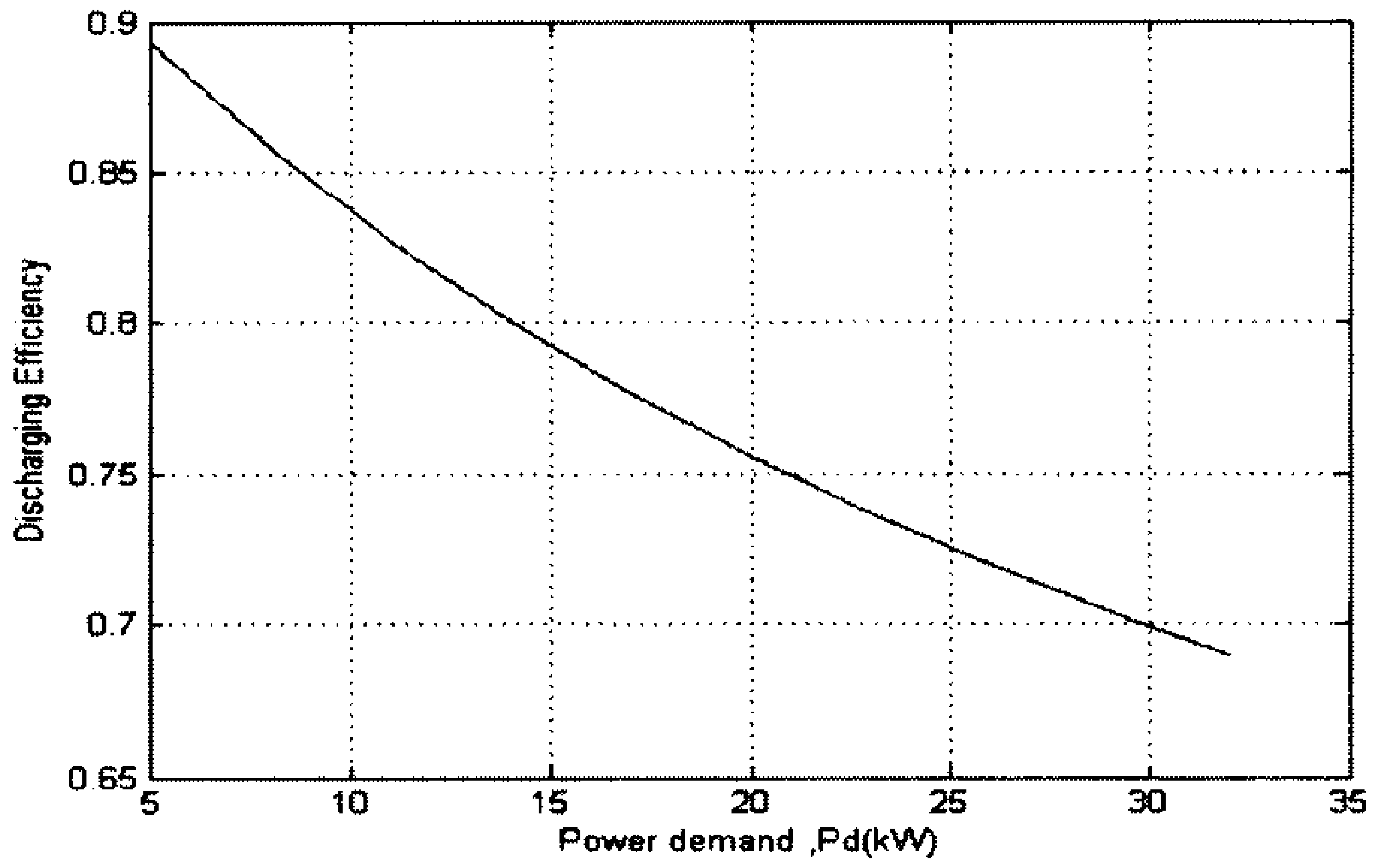


Fig. 7. Plot of Power demand versus Discharging Efficiency

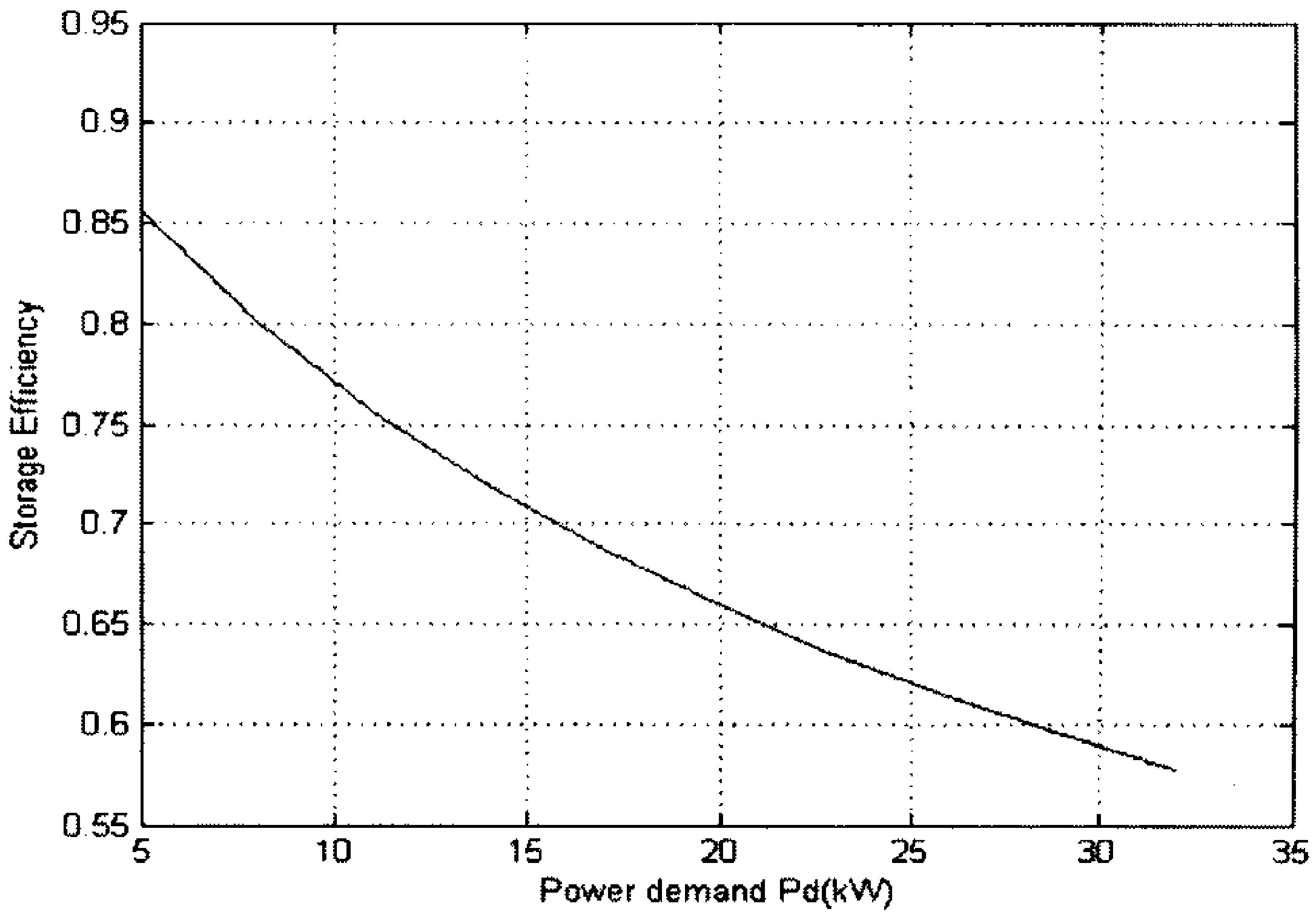


Fig. 8. Plot of Power demand versus Storage Efficiency

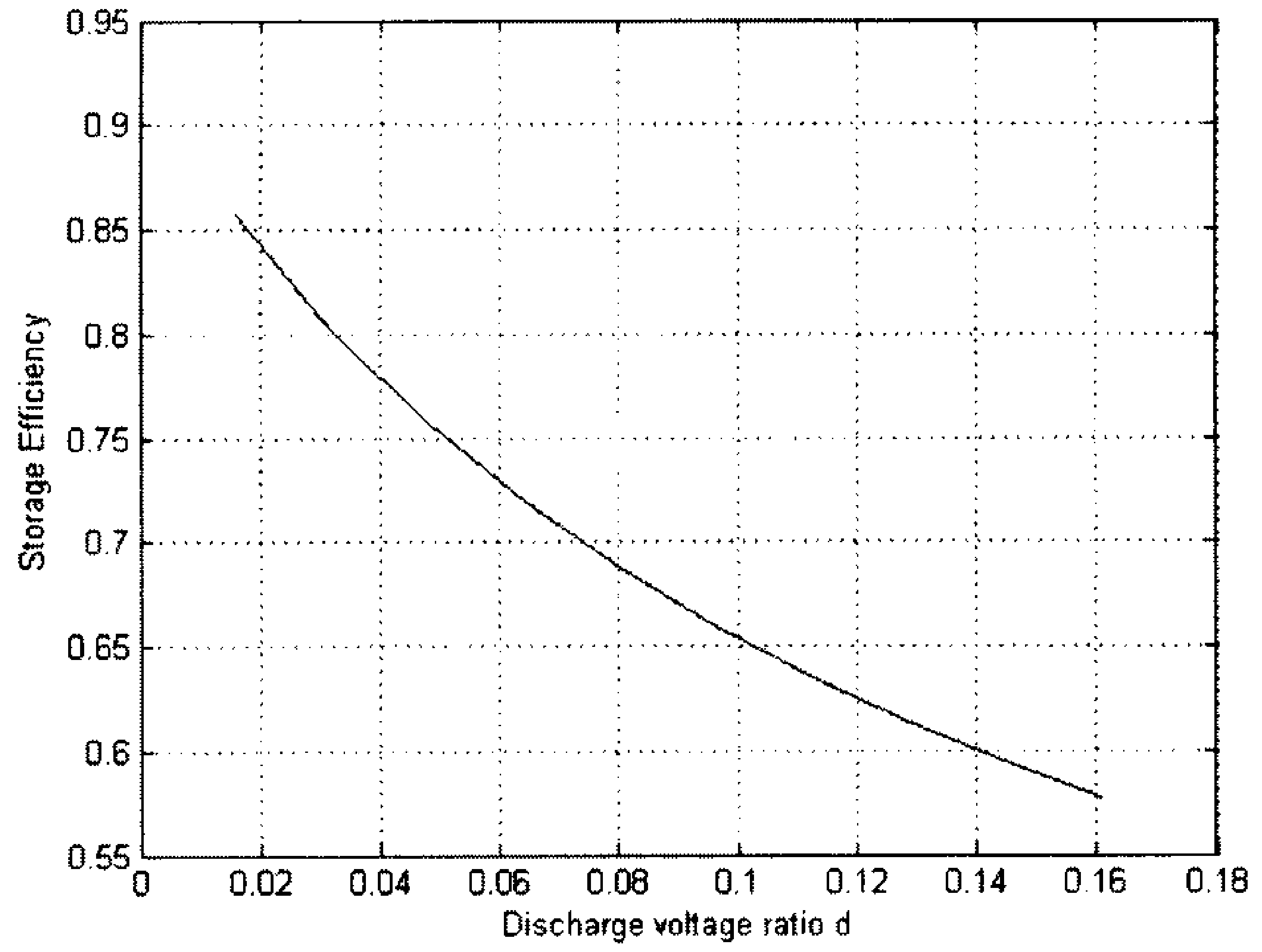


Fig. 9. Plot of Discharge voltage ratio versus Storage Efficiency

4. CONCLUSIONS

The SCESS designed for energy stabilization and maintaining the voltage profile of power distribution system via inverter is of 50 kWh (180 MJ), 440 V voltages and peak power of 30 kW. The design gives the required number of series and parallel combination of supercapacitors in the storage system. The supercapacitors energy storage system can supply the instantaneous power for the back up the loads even though the voltage may drop up to 100 V; this SCESS can back up the load from 1.60-9.9974 hours depending upon the power demand while maintaining the minimum discharge voltage ratio and availability of useful energy , if the charging power is maintained constant at 2kW for this case the charging efficiency is quite good 95.89% and the discharging efficiency is 89.32% while the storage cycle efficiency would be 85.65% . The SCESS can supply energy to the line no of hours in case of steady demand. As the cost of the supercapacitors is predicted to fall with the time, it is independent of charging and discharging cycle, life is very much high and efficiency is also quite high so the SCESS will prove a good option with the non conventional sources for energy stabilization purpose and deferment of the expansion of transmission as well as distribution line.

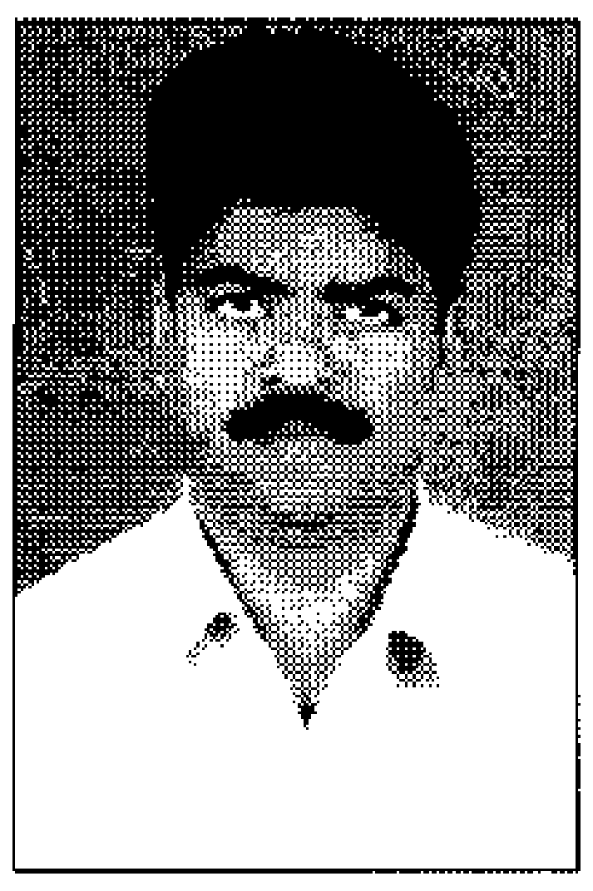
REFERENCES

1. http://leiwww.epfl.ch/publications/barrade_anae_03.pdf P.Barrade, *Energy storage and applications with Supercapacitor.*
2. Jiang Zhang: *Research on Super Capacitor Energy Storage System for Power Network.* 2005, IEEE PEDS Conference pp.1366–1369.
3. Pasko S., Biskup T., Buehrer C., Grzesik B., Roest-Krijgsman J., Michalak J., Stepien M., Zygmanowski M.: *Comparison of SMES and SCES based power conditioning systems.* Power Electronics and Applications, 2005 European Conference on 11-14 Sept. 2005, Page(s):10 pp.
4. Yao Y.Y., Zhang D.L., Xu D.G.: *A Study of Supercapacitors Parameters and Characteristics.* Power System Technology, 2006, PowerCon 2006, International Conference on Oct. 2006, Page(s):1–4.
5. http://www.mitre.org/tech/nanotech , Marin S.Halper and James C. Ellenbogen: *Supercapacitors Brief Overview.* March 2006, pp.1–26.
6. Rufer Alfred, Hotellier D., and Barrade Philippe: *A Supercapacitor-Based Energy Storage Substation for Voltage Compensation In Weak transportation Networks.* IEEE transactions on Power Delivery, April 2004, Vol.19 N0.2.
7. Kuldeep Sahay, Bharti Dwivedi: *Energy storage Technology for Performance Enhancement of Power Systems.* Electrical Power Quality & Utilization Magazine Volume 4, Issue 1, March 2009, Page(s): 1–12.

Tabela 3. ES TD 2005/2006

Sl. No.	Parameters	Analysis	Result
1	Voltage drop Vmin (V)	The voltage may drop up to 100 Volts.	10-100
2	Number of cells connected in series *Ns*	Depends upon the unit cell voltage and required voltage level.	5
3	Number of parallel branches N_p	Depends upon the energy demand capacity.	74
4	Total Number supercapacitor connected in bank NT	Depends upon the *Np* and *Ns*.	370
5	Equivalent capacitance of Bank *Ceq* (F)	Depends upon the maximum energy design criteria.	930.512
6	Equivalent resistance of Bank Req (Ω)	Depends upon the series parallel combination of supercapacitors.	0.012
7	Useful Energy *Eu* (kWh)	The useful energy depends basically upon discharge voltage ratio.	48.708-49.987 for voltage discharge ratio 1.61-16.08%.
8	Minimum discharge voltage ratio dmin	Depends upon the power and energy demand.	The storage can be allowed to discharge for fulfilling the minimum discharge criteria from 0.0040-0.0100.
9	Back-up time tup (hour)	Depends upon the power demand by the consumers.	1.60-9.9974, for 30 kW peak power to 5 kW power demand.
10	Charging efficiency	Basically depends upon charging power and discharge voltage ratio i.e. as charging power is less and charging of bank progresses the efficiency rises.	83.74-95.89%
11	Discharging efficiency	Basically depends upon discharge power (Pd) and discharge voltage ratio i.e. as the more power is discharged and also discharge voltage ratio increases discharge efficiency decreases.	89.32-68.96%
12	Storage efficiency	The storage efficiency of SCESS depends on average charging and discharging efficiency for the cycle.	85.65- 57.75%

8. Dandan Zhang, Man Luo, Jin Li, Junjia He: *Surveying into some aspects of internal resistance of super capacitor*. Electrical Insulation and Dielectric Phenomena, 2005, CEIDP '05.2005, Annual Report Conferenceon 16-19 Oct. 2005, Page(s):637–640.
9. Ji-Yan Zou, Li Zhang, Jin-Yan Song: *Development of the 40 V hybrid super-capacitor unit.* Magnetic, IEEE Transactions on Volume 41, Issue 1, Part 2, Jan. 2005, Page(s): 294–298.
10. Yao Y.Y., Zhang, D.L., Xu D.G.: *A Study of Supercapacitors Parameters and Characteristics*. Power System Technology, 2006, PowerCon 2006, International Conference on Oct. 2006, Page(s): 1–4.
11. www.powerstar.com
12. www.panasonic.com
13. www.maxwell.com
14. www.vina.co.kr/new_html
15. www.nesscap.com/products_lineup_html
16. www.electronicsweekly.com/articles
17. Degobert Ph., Kreuawan S., Guillaud X.: *Use of super capacitors to reduce the fast fluctuations of power of a hybrid system composed of photovoltaic and micro turbine*. Ower Electronics, Electrical Drives, Automation and Motion, 2006, SPEEDAM2006, International Symposium on May, 23rd-26th, 2006, Page(s): 1223–1227.
18. Zhongdong Yin, Minxiao Han, Yunlong Du, Zheran Zhang: *A Practical Approach for Ride Through of Super Capacitor Energy Storage Based ASD System*. PES TD 2005/2006, May 21-24, 2006, Page(s): 744–746.
19. Chad Abbey and Geza Joos: *Supercapacitor Energy Storage for Wind Energy Applications*. IEEE transactions on industry applications, May/June 2007, vol.43, No.3.
20. Yonghua Cheng, Joeri Van Mierlo, Peter Van Den Bossche and Philippe Lataire: *Using Super Capacitor Based Energy Storage to Improve Power Quality in Distributed Power Generation*. EPE-PEMC 2006, Portoroz Slovenia conference IEEE pp.537–543.



Kuldeep Sahay

is Assistant Professor in the Electrical Engineering Department of the Institute of Engineering & Technology, Sitapur Road, Lucknow, Uttar Pradesh, India. He received the Master of Technology from IIT-Delhi and he is presently working for the award of Ph.D. in the area of the energy storage technology application in electric power system .He has published as an author a book and many scientific papers.

Address:
Department of Electrical Engineering
Institute of Engineering & Technology, Lucknow,
Uttar Pradesh, India.
Tel.:+919415061565
e-mail:ksahay.iitd@gmail.com

Dr. Bharti Dwivedi

is Professor & Head in the Electrical Engineering Department of the Institute of Engineering and Technology, Sitapur Road, Lucknow, U.P., India. Her area of interest includes ANN, Energy Storage Technologies & Power Quality Improvement.

Address:
Department of Electrical Engineering
Institute of Engineering & Technology, Lucknow, Uttar Pradesh, India.
Phone: +915224048747.
Email ID: bharti_dwivedi@yahoo.co.in.