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Impact of Distributed Generation over Power Losses on Distribution System

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***Abstract*— This paper is an intent to quantify the impact of distributed generation (DG) over active and reactive power losses on distribution system. The novelty of this paper is the use of new a relevant index: DG penetration level, DG dispersion and DG technologies. Several simulations over a simple distribution system were done. Implications about location and size of DG units were considered using penetration (all scenarios possible) and dispersion levels (including utopian scenarios). Reactive and voltage support capacity was considered, including relative consumption as inductions generators (IG). Simulations over a test distribution system (11.47 kV) representative of Kumamoto area, Japan, were developed using a Matlab™ program coded including specific technologies models. Minimum losses profiles was obtained with better reactive capacity support**

Keywords; power losses; distributed generation, distribution system.

I. INTRODUCTION

Evolutionary changes in the regulatory (stimulating the competence) and operational climate of traditional electric utilities and the emergence of smaller generating systems such as micro turbines have opened new opportunities for on-site power generation by electricity users [1], [3]. Moreover the electric market growth, the financial market's development and the accelerated technical progress have made the optimum size in new investments in generation to decrease, in relation to the market's size and to the private financial capacity [2]. As a result, there have appeared new conditions in the generation sector, making it able to be co-ordinated by the market [1], [4].

In this context, distributed energy resources (DER) - small power generators typically located at users' sites where the energy (both electric and thermal) they generate is used - have emerged as a promising option to meet growing customer needs for electric power with an emphasis on reliability and power quality [3].

Distributed generation may have a significant impact on the system and equipment operation in terms of steady-state operation, dynamic operation, reliability, power quality, stability and safety for both customers and electricity suppliers. This impact may manifest itself either positively or negatively, depending on the distribution system, distributed generator and load characteristics [5]-[7]. The main objective of the study has been to quantify the impact (increase or decrease) that DG produces on losses on distribution networks considering several aspects.

II. METHODOLOGY

Technical power losses are consequents of transport of electricity by the networks, between generators to transmission/distribution system. Technical losses are a part of electrical power losses of system, resulting of: losses on transmission devices, losses for corona effect, iron losses on transformers, losses by eddy currents, and dielectric losses. In this paper, we are focused only on technical losses caused by transport of electricity.

Original distribution networks were originally designed to be *passive*, deliver power from the more heavily reinforced transmission system to consumers, real and reactive power generally flowing towards the edge of the system, in the direction of the voltage gradient. Integrating distributed generators to operate in parallel with the existing system results in an active network with the possibility of bidirectional power flows (depending on loading conditions), a change in losses and variations in voltage.

The main objective of the study has been to quantify the impact (increase or decrease) that DG produces on losses on distribution networks considering several aspects. These aspects are:

A. Penetration Level

The penetration level (%*DGlevel*) can be calculated as a function of the total DG power generation (P_{DG}), or the total of generation factor times DG installed capacity, over the peak load demand (P_{load}).

$$\%DGlevel = \frac{P_{DG}}{P_{load}} \times 100\% \qquad (1)$$

Just centralized generation is equivalent to 0% of penetration level, meantime 100% describe al load demand cover by distributed generators ($P_{DG} = P_{load}$).

Considering penetration level indicator, we define several scenarios:

- *Low Penetration Scenario*: Consider penetration level below 30%. Low penetration level consider a scenario of conservative integration market, with high economical and technical barriers than make no attractive to consumer use DG (P_{GD}<$0.3P_{load}$).
- *Semi-Ideal Penetration Scenario*. Distributed generation capacity in this scenario correspond half of load demand. Liberalized market will be adequate to this penetration level ($P_{GD}=0.5P_{load}$).
- *Ideal Scenario*. Consider complete penetration of DG, all load will be supplied by DG ($P_{DG}=P_{load}$). This scenario minimizes power production by centralized generator. Completely open market will be able to make possible high penetration levels like this.
- *Utopist Scenario*. DG capacity will be over load demand; in this case, power flow will be reversed. Distribution network will export power to the grid (P_{GD}>P_{load}).

B. Dispersion Level

Dispersion level of DG (%*DGdispersion*) is ratio of number of nodes in which there is DG (#*BusGD*) and the number of nodes in which consumption exists (#*BusLoad*).

$$\%DGdispersion = \frac{\#BusGD}{\#BusLoad} \times 100\% \qquad (2)$$

When dispersion level is 0%, just centralized generator is connected to distribution system, and 100% mean all nodes with load have a DG (#*BusGD* = #*BusLoad*). In this paper we consider following scenarios:

- *Low Dispersion Scenario:* Consider a level below 30%. Situation appellant and easily attainable in a not liberalized environment (#*BusGD* = 30% #*BusLoad*).
- *Semi-Ideal Dispersion Scenario:* DG is installed on half of load buses. This scenario consider incentive to consumer to install DG (#*BusGD* = 50% #*BusLoad*).
- *Ideal Dispersion Level:* This scenario considers total dispersion of DG unit. All load buses have DG. Completely open and liberated market with great incentives to install DG by the consumers (#*BusGD* = #*BusLoad*).

C. DG Technologies

DG units include wide portfolio of technologies (gas turbine, reciprocate engines, wind turbines, microtrubines, photovoltaic, fuel cells, bio-energy). These technologies would be including on three categories: Synchronous Machines, Asynchronous machines, and Power electronic interface. Nevertheless, we are interested on technical power losses an inherent steady state phenomenon. In this case, we decide use steady state capacity of DG technology to voltage support and reactive power capacity and then we consider:

- *Constant power factor operation*. Consider non reactive control on DG unit. Limited reactive generation could be included. This case is similar of some power electronic interface.
- *Variable power factor operation*. Some DG technologies include reactive generation capacity with limits as micro turbine or some wind turbines with power converters.
- *Reactive power consumption* (induction generators). These DG technologies include a reactive power consumptions meantime produce active power. This case is typical of squirrel cage induction generator as first generator wind turbines.

D. Total Technnical Losses Index

A major potential benefit offered by DG is the reduction in electrical line losses. The loss can be significant under heavy load conditions. The utility is forced to pass the cost of electrical line losses to all customers in terms of higher energy cost. With the inclusion of DG, line loss in the distribution system can be modified.

To evaluate total losses we defined line losses index (*LLI*) as:

$$LLI = \frac{LL_{wDG}}{LL_{woDG}} \qquad (3)$$

where LL_{wDG} is total line losses in the system with DG and LL_{woDG} is the total line losses in the system without DG.

III. Modeling

This section describes the models that were used.

A. Network

A typical distribution system was used for simulations in this paper. This is a representative distribution feeder of Kumamoto area on Japan [8] (Fig 1).

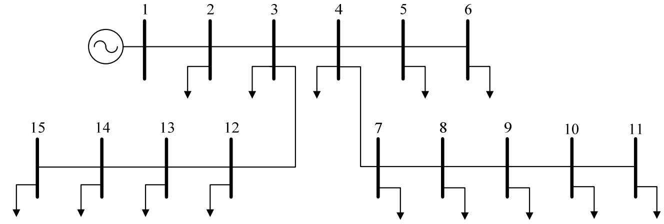

Figure 1. Test System

TABLE I. LINEAS AND LOAD DATA FOR TEST SYSTEM [8]

From Bus	To Bus	R (p.u)	X (p.u)	B (p.u)	P_{load} (p.u)	Q_{load} (p.u)
1	2	0.00315	0.075207	0.00000	0.02080	0.0021
2	3	0.00033	0.001849	0.00150	0.04950	0.0051
3	4	0.00667	0.030808	0.03525	0.09580	0.0098
4	5	0.00579	0.014949	0.00250	0.04420	0.0045
5	6	0.01414	0.036547	0.00000	0.01130	0.0012
4	7	0.00800	0.036961	0.03120	0.06380	0.0066
7	8	0.00900	0.041575	0.00000	0.03230	0.0033
8	9	0.00700	0.032346	0.00150	0.02130	0.0022
9	10	0.00367	0.01694	0.00350	0.02800	0.0029
10	11	0.00900	0.041575	0.00200	0.21700	0.0022
3	12	0.02750	0.127043	0.00000	0.01320	0.0014
12	13	0.03150	0.081405	0.00000	0.00290	0.0003
13	14	0.03965	0.102984	0.00000	0.01610	0.0016
14	15	0.01061	0.004153	0.00000	0.01390	0.0014

Voltage Base: 11.432 kV, Power Base: 30 MVA

1) Modelling of network

Model of network is based on topology data of real medium voltage networks (Table I). $R + jX$ modeling was used for all cables using real data and capacitive susceptance, B was include where necessary. The slack node is the feeder header. The effect of feeders connected to the same bus bar has not been considered.

2) Modelling of load demand

Model of load is based on nominal power. Load buses are considered as a PQ node with cos ϕ depending of real data. They are modeled as constant power load, that is, independent of voltage level. This has been considered irrelevant at this stage of the study.

B. DG Units

1) Constant Power Factor Operation

In this DG unit active power generated (P_g) and reactive power satisfy (Q_g):

$$\frac{P_g}{\sqrt{P_g^2 + Q_g^2}} = \cos\phi \qquad (4)$$

Where cos ϕ is the constant power factor. Two important aspect limits this operation mode: (a) nominal capacity (VA) never be violated, (b) power factor would be remain constant as eq (4).

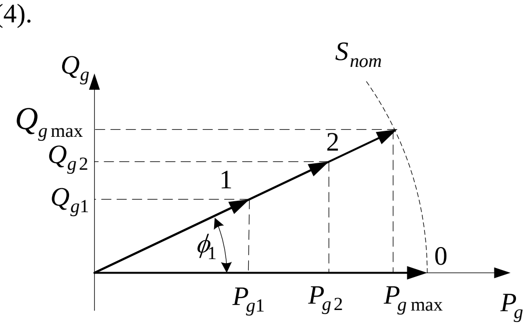

Figure 2. Constant Power Factor Operation of DG Unit

2) Variable Power Factor Operation

Operation of DG unit on variable power factor, permits support of voltage by reactive power generation.

In this mode, reactive power generation (Q_g) is limited only by the nominal capacity (S_n) of DG unit, and satisfy:

$$Q_g = \sqrt{\left(S_{nom} sen\left(\cos^{-1}\left(\frac{P_g}{S_{nom}}\right)\right)\right)^2 - P_g^2} \qquad (5)$$

An example of variable power factor operation is shown on Figure 3.

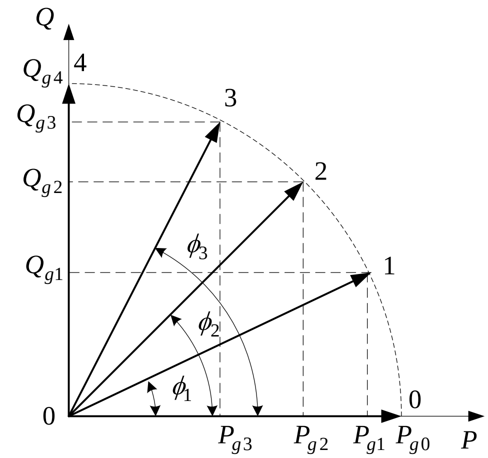

Figure 3. Variable Power Factor Operation of DG Unit

3) Reactive Power Consumtion

Reactive power consumption of DG units is representative of squirrel cage induction generator. For steady state simulations we are use the famous Stainmetz model for induction machine (Fig 4).

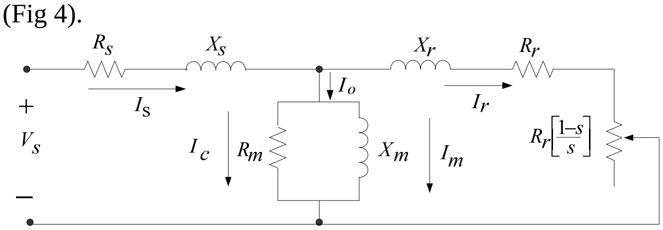

Figure 4. Steady State Model for Squirrel Cage Induction Generator

This model was included on one power flow program developed by the author in Matlab®. Iterative method of Newton-Raphson with RX model was employed in this paper [9], with a classical squirrel cage induction generator used for wind turbines (Table II).

TABLE II. SQUIRREL CAGE INDUCTION GENERATOR PARAMETRER [10]

Parameter	Variable	Value
Stator Resistance	R_s	0.00571
Stator Reactance	X_s	0.18780
Rotor Resistance	R_r	0.00612
Rotor Reactance	X_r	0.06390
Magnetizing Reactance	X_m	2.78000

IV. SIMULATIONS

Using a Matlab® program developed by the author simulations over test system in all scenarios was performed. All simulations were developed with Newton-Raphson iterative method with maximum error of 10^{-4} p.u. In each case, consideration about DG unit was performed; and for induction generator detailed model was used including RX model presented in [9]

A. Base Case

Initially a standard load flow was performed over tests system, in base case, with P_{load} = 18.903 MW y Q_{load} = 1.338 MVAr (0.6301+0.0446*j* p.u). Just centralized generation was considered on bus 1, with a power generation of P_{gen} = 19.0966 MW, Q_{gen}= 0.675894 MVAR (0.6366+ 0.0225*j* p.u).

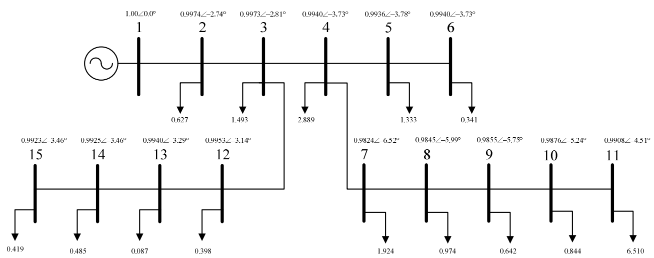

Figure 5. Base Case for test system load flow

In this case, technical power losses was found P_{losses} = 0.193562 MW Q_{losses} = -0.662106 MVAr (en por unidad 0.0065-0.0221*j* p.u); from this losses in per unit, total technical losses for transmission system without DG was: LL_{woDG} = 0.0065 p.u.

B. Scenarios

To evaluate the impact of DG over losses in distribution system, several scenarios was simulated. For penetration level simulations was Developer from 0% to 150% (see Table 2). *Low Penetration Scenario*: Consider penetration levels of 10%, 20% and 30% (Cases *I*, *II* and *III*). *Semi-Ideal Penetration Scenario*. DG units to cover half of load demand. (Case *IV*). *Ideal Scenario*. Consider complete penetration of DG (Case *V*). *Utopist Scenario*. DG capacity will be over load demand; in this case, power flow will be reversed. (Case *VI*).

TABLE III. ELEMENTAL CHARACTERISTIC OF PENETRATION SCENARIES

Case	Penetration Level	P_{DG} [MW]	Name of Identification Case
VI	150.0%	28.3545	Utopic
V	100.0%	18.9030	Ideal
IV	50.0%	9.4515	Semi-Ideal
III	30.0%	5.6709	III
II	20.0%	3.7806	II
I	10.0%	1.8903	I

A wide range of dispersion level was considered: *Low Dispersion Scenario:* Consider levels of 21%, 28% (*A* y *B*). *Semi-Ideal Dispersion Scenario:* DG is installed on half of load buses (case *C*). *Ideal Dispersion Level:* All load buses have DG. (*D*)

TABLE IV. ELEMENTAL CHARACTERISTIC OF DISPERSION SCENARIES

Case	Dispersion Level	Number of Bus with DG	Nombre de Identificación del Caso
D	100.000%	14	Ideal
C	50.000%	7	Semi-Ideal
B	28.571%	4	Low Dispersion
A	21.429%	3	Low Dispersion

C. Priority order and Dispatch

Simple criteria to consider priority order of integration of DG units is consider by power demand on bus. In this case the first bus with DG is most loaded bus. Power dispatch for each DG unit is function of *weight factor* (ϑ_{DG}), that consider penetration level (*%DGlevel*) to be attend and this is proportional to load demand connected on bus (P_{loadi}). Table V shown an example of active power generated by unit for 21 % of penetration levels.

TABLE V. ACTIVE POWER TO BE GENERATED [MW] TO 21% OF PENETRATION LEVEL: LOW DISPERSION. CASE A

Penetration Level	I 100%	II 50%	III 30%	IV 20%	V 10%
11	1.089	2.178	3.267	5.446	10.892
4	0.480	0.961	1.442	2.404	4.808
7	0.320	0.640	0.9607	1.601	3.202

V. RESULTS

A. Constant Power Factor

To evaluate the impact over technical power losses of DG units operating on constant power factor, simulation was developed for cos ϕ = 1.0, 0.9 and 0.8 leading power factor.

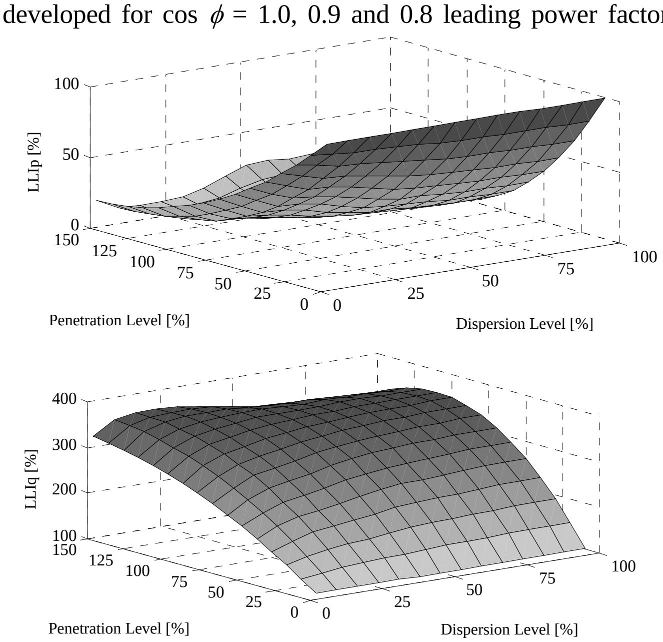

Figure 6. Total Technnical Losses Index for several penetation and dispersion levels. DG unit operating cos ϕ = 1.0

The behavior of total technical losses index (*LLI*) for all possible scenarios considered are visible on Fig. 6, active and reactive power for DG units operation on constant power factor cos ϕ = 1.0. Space limitation do not permit include results for other power factors; 0.8 y 0.9. LLI_p exhibit a behavior like a "*bathtub curve*", and convex form for LLI_q. For low penetration level, active power losses decrease but for higher penetration level losses marginally increase and even can be higher than losses in base case. Better losses behaviors are found with power factor bellow unitary (Fig 7). Reactive capacitive support of DG units permit reduces active power losses, but antagonistic behavior is found in reactive power losses increasing the maximum value (Fig. 7).

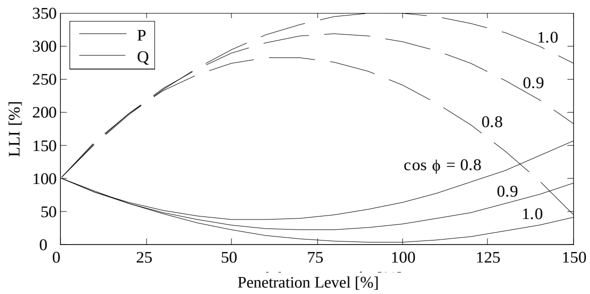

Figure 7. Total Technnical Losses Index versus penetration level for several DG power factor for 100% dispesion level

Increases on dispersion levels reduce the minimum of LLI_p, and increase the penetration level where it's found (for a constant power factor operation); and increase the maximum LLI_q (Fig. 8).

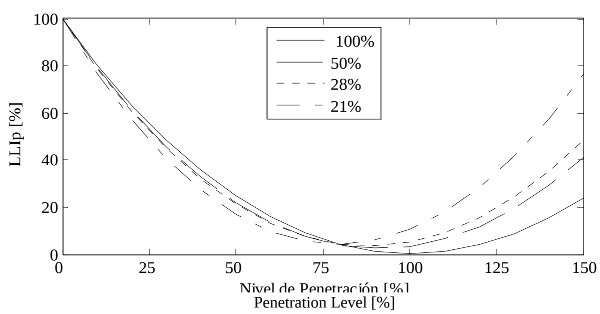

Figure 8. Total Technnical Losses Index versus penetration level for several dispersion levels (21, 28, 50 and 100%) cos ϕ = 1.0

Locus of minimum active power losses (ILL_p) and maximum reactive power losses (ILL_q) was plotted. Increase on power factor operation results in minimum ILL_p for high dispersion levels, but increase the maximum value of ILL_q (Fig 9).

B. *Variable Power Factor*

DG units operating on variable power factor, produce a completely different behavior of active and reactive power losses of bathtub curve. In this mode, increasing penetration level reduce ILL_p an this effect is more dominant at high low dispersion level. In reactive power losses and increase of penetration level increase ILL_q and dispersion level help to reduce this effect (Fig. 10).

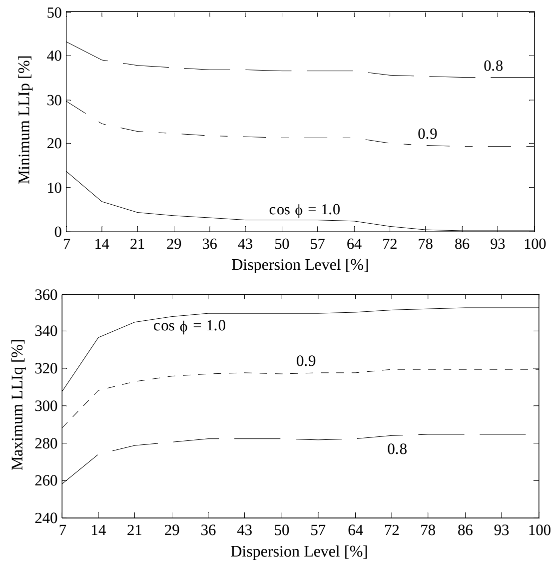

Figure 9. Minimun ILLp and Maximum ILLq versus dispersion level for several power factor

Variable power factor operation, permits reactive power generation but depends of the active power generation; this reactive capacitive is limits by the nominal power of DG unit. This complementary function of reactive power generation is maximum on minimum active power generation.

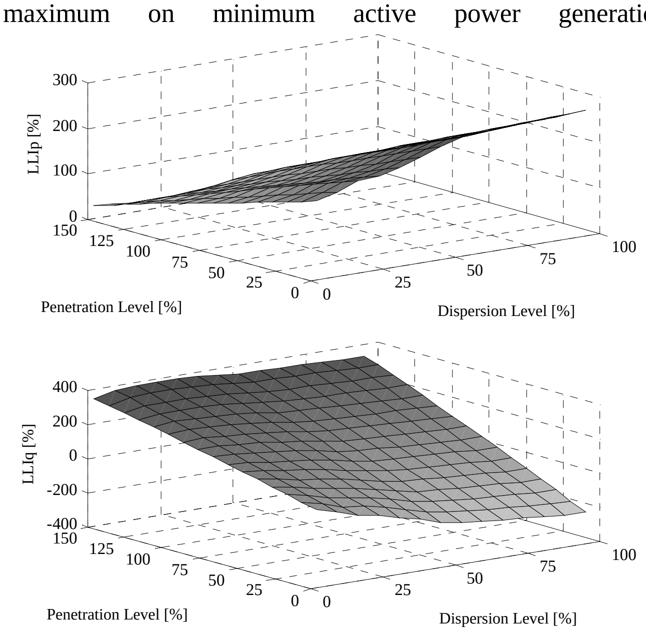

Figure 10. Total Technnical Losses Index for several penetation and dispersion levels. DG unit operating variable power factor

C. *Reactive Power Consumtion*

Some DG technologies consume reactive power during active power production. Typical example of such technologies is squirrel cage induction generator directly connected to the grid. Reactive power consumption of this type of DG is function of voltage. IG connected to distribution system imposes a exceptional requirement of reactive power from the centralized generators. Frequently, local power factor compensation is utilized to voltage support and reactive power consumption of IG. In this simulation worst case, without power factor compensation was considered. Again, *bathtub* curve is found on ILL_p behavior versus penetration and dispersion level (Fig. 11). In ILL_q, a convex curve show antagonist behavior respect active power losses.

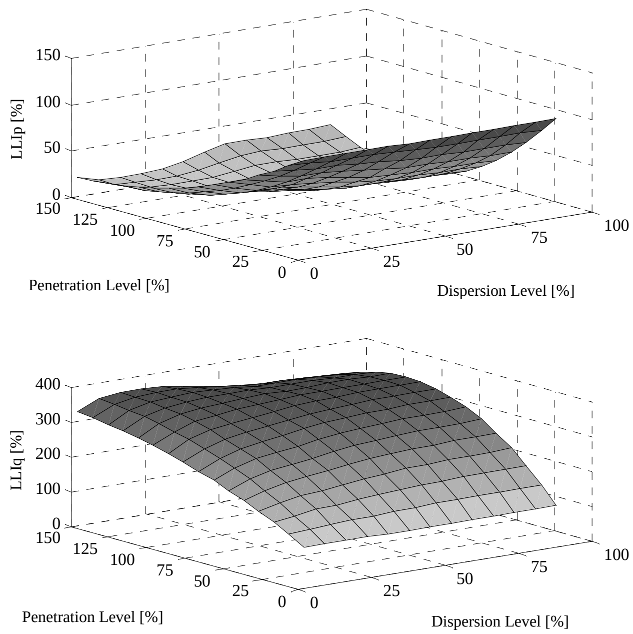

Figure 11. Total Technnical Losses Index for several penetation and dispersion levels. DG unit with consumtion of reactive power, induction generators

Reactive power losses show maximum values on high penetration levels and low dispersion levels.

VI. Conclusions

A wide range of simulation over a typical distribution system, considering different reactive power capacity con DG units. In constant power factor and reactive power consumptions (IG) technologies, active power losses variation on distribution networks due to DG has a sort of "bathtub curve" behavior. In general, for low DG penetration level, losses decrease but for higher penetration level losses marginally increase and even can be higher than losses in base case. This effect is more dominant in low dispersion level. Reactive power losses curve is convex with maximum values to high penetration level and more evident on low dispersion level.

Minimum active power losses levels are reached with high penetration levels if DG is sufficiently dispersed; and reactive power generation capacity is enough. In variable power factor operation, active power losses decrease with high [penetration levels and low dispersion level, contrary situation is found on reactive power losses.

Results evident from this paper that controlling reactive power supplied by DG has a big impact on technical power losses of distribution. In GD unit based on IG need a sophisticated control but a simple scheme can be implemented; as local power factor correction.

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