2. Dynamic Load Model in Power System

Problems in Power System Model

Various Calculations and simulations are performed in scientific field. A maxim says that wise man learns from history, while not wise man learns from experience. Scientific way that supposes various theories (i. e. hypotheses) from past measured data and observed facts for needs of human civilization certainly learns from history like wise man. To perform those calculations or simulations real phenomena must be translated to mathematical models for calculations or simulations. Model is not mare data but relations between data. Expressing the relations as equations mathematical model are build.

Computers are generally used in modern Scientific and engineering fields for fast and large scale calculations. Of course hardware is a mare box, and application software makes the box as powerful computer. The application software is sometimes called as “tool”, which means a convenient tool for calculation. The tool assumes model prepared in mathematic form. Thus, modern scientific and engineering calculations need two main actors that are tool and model.

There are “elegant” calculation and “muscling” calculation. Both of them need tool and model. Computer based calculation is typical muscling calculation, and tool is more important actor. In power system engineering laboratory of Japanese university, main studying way is to build up tools. Professors say so. Although model has equal importance as tool in scientific and engineering calculation, model seems not to be respected in university education.

After graduated university, engineers perform calculations as occupation using tools for general use. Since those tools are used many people, are rapidly refined if defects are found, and are always kept reliable. On the contrary, since models are different by objects, engineers, and so on, they are not kept so reliable as tools. When simulation were begun to be adopted around 30 years ago, the fact that the calculation was performed by computer simulation was the basis of credit. But nowadays, simulation has lost the creditable position and means almost false.

Perhaps reliability of simulation tools is better or equal as 30 years ago. Therefore, they are not tools but models that had spoiled credit of simulation. In addition, wrong using of simulation, wrong selection of case, and wrong assertion through simulation are also spoil credit, but it is seen in not only simulation but also everything. Therefore, it is not discussed here. Main theme of the chapter is what problems had spoiled credit of simulation.

Load behavior is Blind Spot

Since most power source and grid are owned by utility, so long as not annoy customers, any field test can be performed. Therefore, character of power source machines and grid equipments are quite well understood. On the contrary, as to power system load, load equipments are owned and operated by customers, and tests are almost impossible. As the result, load character is not well understood not only in old days but also even in today, and is still staying as a blind nowadays.

The author had noticed the blind spot in 1985 by two phenomena observed. The first is introduced in Fig.2.1. This is the record of RMS voltage at nearby substation when one of two circuits of transmission lines tipped due to a three-phase-to-ground fault. One circuit still survived, so outage is avoided. However, deep voltage sag is observed.

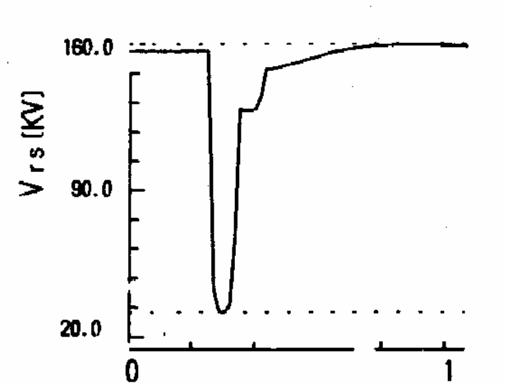

Fig. 2.1 delayed voltage recovery due to fault

According to ordinary knowledge, voltage will recover to normal value at the instance that the faulted circuit was switched off (0.1 sec after the fault has occurred in the figure). However, measured data tell that slight low voltage follows around 0.1 sec after the fault is cleared and complete voltage recovery needs some time.

The second is introduced in Fig. 2.2. This is voltage waves of phase A, B, C, and zero sequence recorded in a substation when it was shut down due to one-phase-to-ground fault on the same phase of two-circuit transmission line feeding to the substation. Voltage wave of phase B goes to zero during faulted 0.1 sec (6 voltage waves) and magnitude of A and C phases increase. This is a typical grounded fault.

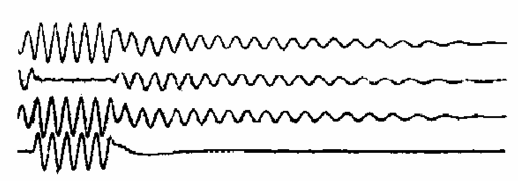

Fig. 2.2 Delay in voltage fade out

According to ordinary knowledge, voltage of the substation will become zero at the instant of disconnection. However in this case, voltage of the substation fades out slowly within around 0.4 sec. This phenomenon may be observed if considerable power source exists under the substation. But such generator or customer owned generator does not exist.

In power system engineering, many predictive calculations are performed. Main purpose is to maintain reliability of power system considering undesirable natural phenomena such as lightning attack. Calculation must represent truth at least. However, the two measured phenomena introduced here were not able to be represented by simulation based on traditional model. Therefore, field engineers in those days judged the phenomena as serious and consulted to the author.

Why those phenomena were judged as serious? The reason is that science narrowly understands real phenomena based on few “truth” and many “hypothesis”. As to the hypothesis, Karl popper, one of great science philosophers in 20^{th} century revealed that scientifically hypothesis must be falsifiable. It is the scientific attitude to accept that the hypothesis is false if only one truth that falsifies the hypothesis is discovered. And of course, scientific hypothesis must be written not only logically but also falsifiable.

That is, field engineers in those days became uneasy whether calculation methods they used were really reliable or not, because the two observed phenomena were not able to be represented by those methods. Although field engineers in 1985 must not know Karl Popper, they chose scientifically right way. Nowadays, the author regards virtue, which has both meaning of ability and ethics, of field engineers in those days as admirable.

The author, shown the two phenomena, already had a hypothesis. Considerable amount of induction motor (IM) is included in load that means assembly of electric equipments that customers use. In spite of the truth, traditional calculation method assumed the “old hypothesis” that IM does not exist in load. The author recalculated by “new hypothesis” that half or more electricity is used in IM, and succeeded to represent the two phenomena. However, measuring equipments in those days had only poor performances and could show only poor information as shown in the two figures introduced. To identify how much amount of IM exists, higher grade measuring equipments were needed. The need was fulfilled in later years, and began to be equipped since 1998. Measured data by the equipments perform quite important role in analyses hereafter.

It must be explained why the author had the hypothesis that considerable amount of IM exists in load. In those days it was planned that much power of large nuclear source outside was imported through tie line since 1987. Tie line connects two power systems. Power flow is set small usually, and much power will flow in emergence for avoiding large blackout. Operational margin of tie line will decrease, if considerable power always flows in tie line even in normal condition. How much operational margin remains? That is very serious question in those days. Problems with much receiving power through tie line are more serious. Voltage instability is the typical problem, and becomes more serious if much amount of IM exists in load.

Finally it was found out that voltage stability was maintained if 280MVA capacitors were equipped for 3000MW peak demand in those days and used in emergence of low voltage as “reactive power reserve”. Those capacitors were introduced in 1985 to 1987, and completed in 1987. Just after the completion in 1987, large blackout due to voltage instability happened in west Kanto, when the author worked in construction of hydro power stations. The author thought that anxiety was realized in another utility and reactive power reserve, which was installed by only one utility employing the author, was proved as indispensable. Thereafter reactive power supply became really recognized as indispensable. However, IM in load were not attended, because cause of the large blackout was anyhow explained by operation of tap changers in transformers. Electric power society in Japan regrettably lost a good opportunity.

History of Dynamic Load Model

Thus electric power society in Japan has been employing “static load model” that ignores IM till recently. “Static” means that real and reactive power consumed in load does not depend on the past and decided by present voltage and frequency only. On the contrary in foreign electric power societies, “dynamic load model”, which means that real and reactive power consumed in load also depends on the past voltage and frequency, is already employed. What dynamic load model is suitable and how influence by past voltage and frequency should be considered have been discussed. Various hypotheses have been proposed. Two main parties held serious discussion in the end of 20th century. It is quite interesting, so introduced here.

The first party employs "Component Based Method" and intends to construct load model as a mixture of existing electric equipments such as heater, motor, light, and so on. Mixture ratio is made by field investigation of customers. IM is most important because it shows most dynamic behavior. The method may be realistic but has some defects. That is the mixture ratio, which varies by season, time, demand, region, and so on. Is the suitable ratio for the individual case study reliably presumed from fewer samples? Opponents criticize the point.

The second party employs "Measurement Based Method" and intends to identify unknown parameters included in *a priori* assumed mathematical function (for example, $P = p(V, f), Q = q(V, f)$) as load model. Most papers employ 1st order lead and lag as the function and measured data of relatively small voltage change such as tap change of transformers for the identification. The method is certainly creditable because measured data are used. However, orthodoxy and legitimacy of the method are questionable because it is not proved yet whether *a priori* assumed mathematical function with parameters presumed from small disturbances also work well in case of large disturbances. Opponents criticize the point.

Long but fruitless controversy had been held between those two parties until the end of 20th century. Ref. (1) and (2) are the typical literatures of the *Measurement Based* method. Serious discussions were made from *Component Based* party. In those papers, volume of discussion sometimes exceeds volume of the paper itself. Those discussions show the difference of the two methods and confusion in those days.

Discussers of the two parties quite well knew defects of their methods. It is desirable to appear the third party that *aufheben* those two methods. A much better load model can be constructed, *if a certain mathematical model can represent physical structure and general nature of existing dynamic loads, and if unknown parameters of the model can be identified by measured data.* Appearance of the third party appears earlier than generally hoped at the end of 20th century. Ref. (3) and (4) are said to be the pioneers. Big names such as *Concordia* and *Pal* have cast positive messages in those discussions. After those two reference papers, dynamic load model has become science.

Today in 21st century, the controversy had already ended. Measurement based was defeated, and IM load model has conquered the world only excluding Japan. In 2008 IEEE General Meeting, FIDVR (Fault-Induced Delayed Voltage Recovery) was introduced as a serious phenomenon and quite well represented by the model of IM behind impedance from observation point to collective load terminal, which is quite similar to the model introduced paper (5) of the author in 2006. However, regular paper has not published yet in US. Thus in most countries, power system analysis using dynamic load model with IM is generally performed.

Belatedly, Ref. (6) and Ref. (9) adopt IM load model recently in Japan. A noteworthy movement is seen. How much percentage of electricity is consumed in IM is identified by field investigation of customers in 2009 to 2010 by Japan government and a private research center independently. The former presumed IM ratio (including inverter driven) as 55% and the latter does as 57%. Since such a large amount of electricity is consumed in IM, its energy efficiency must be increased by adopting so called "top runner way". That is the conclusion of the investigations by Japan Government. While, IM ratio is presumed as 50% without inverter driven by the author. Since IM ratio by the independent three researches agrees very well, reliability of those three researches are said as excellent.

Since it is already known that IM shows quite dynamic behavior and IM ratio is up to 50% or more, it is quite reasonable that power system load are classified and modeled as parallel composite of IM and the others. However, electric power society in Japan seems to have queerly strong antipathy to IM load model. Only in Japan, IM load model has to walk a long way toward the goal, that is world standard.

Dynamic Load Model in Power System

According to discussion above, structure of parallel composite of IM as the most dynamic element, resistor as the most static element, and reactor or capacitor for adjusting power factor of total load as shown in Fig. 2.3is suitable. What can be recorded is behavior only at observation point, which usually locates at secondary bus of primary substation. There exists some impedance on the path from observation point to collective load. The impedance is modeled as Zs in the Figure.

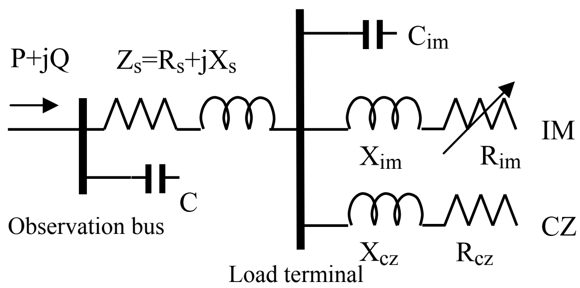

Fig. 2.3 Structure of dynamic load model in power system

In the figure, impedance of induction motor load is expressed as a variable resistance R_{im} behind a constant reactance X_{im} as follows.

$$Z_{im} = R_{im} + j\,X_{im}$$

By same way, impedance of constant impedance load is expressed as series composite of a constant resistance R_{cz} and constant reactance X_{cz} as follows.

$$Z_{cz} = R_{cz} + j\,X_{cz}$$

Impedance of total load as parallel composite of induction motor load and constant impedance load is expressed as a variable resistance R_{all} behind a variable reactance X_{all} as follows.

$$Z_{all} = R_{all} + j\,X_{all}$$

Of course, relationship as follows must be satisfied.

$$\frac{1}{Z_{all}} = \frac{1}{Z_{im}} + \frac{1}{Z_{cz}}$$

Resistance of induction motor load Rim varies from 1 at normal operation condition to 0 at complete stop condition. The other resistance and reactances are kept constant. At normal operation, series reactance is around 10% of load's internal resistance. Then, impedance of total load at normal operation is assumed as 1 + j 0.1. And, motor ratio (how much part of electricity is consumed in motor) assumed as K. When internal resistance of induction motor R_{im} is expressed by normalizing its value in normal operation as 1, impedance of total load at any motor resistance R_{im} can calculated as follows.

$$\frac{1}{Z_{all}} = \frac{K}{R_{im} + j\,0.1} + \frac{1 - K}{1 + j\,0.1}$$

When R_{im} varies 1 to 0, resistance and reactance of total load, R_{all} and X_{all} are calculated as Fig. 2.4. Here, motor ratio is varied as parameter. It is demonstrated in later chapter that internal resistance of stalled induction motor decreases to around 40% of normal operation. Therefore in the figure, 0.4 to 1.0 R_{im} should be noticed. When motor ratio is 50% or more, internal resistance of total load R_{all} is not so much different from that of pure motor load. Series reactance of total load X_{all} is not much varies from 0.1 in the R_{im} range (0.1 to 0.4).

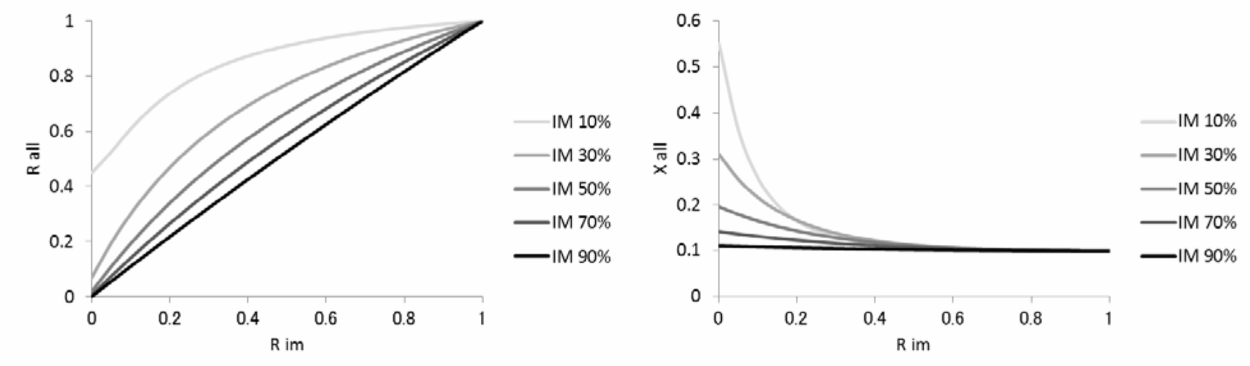

Fig. 2.4 Internal resistance and series reactance of total load

Thus, if motor ratio is 50% or more, characteristics of total load is very close to pure motor load, but is not completely same of pure motor load. Since power consumption by constant impedance load much decreases when voltage drops, motor can receive much power, and deceleration of motor is mitigated. Therefore, when ratio of constant impedance is higher (that is, motor ratio is lower), deceleration of motor becomes slower. But it must be noticed that internal resistance and series reactance of total load with motor ratio 50% is not so much different from those of pure motor load if once decelerated, although deceleration speed is different.

Thinking so, although it is a too serious expression, it is a border line that motor ratio of real load exceeds 50% or not. Therefore, motor ratio of existing load must be investigated. For the purpose, two methods exist. The first is employed by the author. It intends to identify motor load parameters so that measured load's behavior is well represented by simulation. Hereafter, the method is minutely introduced. The second is employed by government's and private investigations. It statistically identify motor ratio by sampling investigation in customers. The two methods have their own unique merits and demerits. However roughly saying, it is the first method that can provide full information of load parameters for power system analyses and simulations.

Instantaneous voltage sag is suitable phenomenon for identifying load parameters, because it is sufficiently large disturbance and its number of measured data is large enough. A lightning attacks 2-circuit transmission line. 1 circuit trips due to the lightning. Since the other circuit survives outage is avoided, but system voltage considerably drops in a short time (around 0.1 sec) till the faulted circuit is cut off. Load responds to voltage sag. Voltage sag data by fault outside of studied load must be employed for load parameter identification. In case of inside fault, voltage may drop at some area inside much more than observation point and much identification error may be generated.

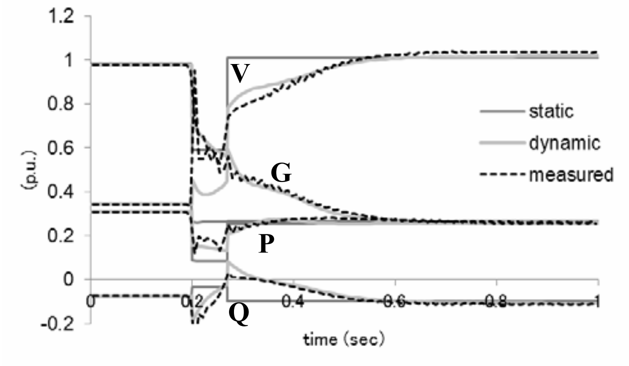

Fig. 2.5 Represented voltage sag by giving fault

Load parameter
- Static model
  - α = 1.0
  - β = 2.0
- Dynamic model
  - IM ratio　70%
  - IM inertia　0.5sec
  - IM loading　50%

Calculation result by giving fault of recorded type fault at fault point identified fault locator on the model of large power system is shown in Fig. 2.5. Static load model that is widely adopted in Japan assumes active and reactive powers are decided by voltage and frequency at the instant as follows.

$$P(t) \propto V(t)^{\alpha} f(t)^2 , \quad Q(t) \propto V(t)^{\beta}$$

Parameters are usually chosen as $\alpha = 1$ and $\beta = 2$, and they are also used here. In the figure, voltage V, conductance seen from observation point G, active power P, and reactive power Q are drawn in square forms in case of static load model, and never agree with measured data. Therefore, “static load model” hypothesis is falsified, and its life as hypothesis has ended scientifically. However, the hypothesis still survives in Japan yet. The reason is not known.

Dynamic load model with IM represents real phenomena considerably but minutely seeing some differences are seen. Because, the other load exist around the studied load, and they may affect identified parameters.

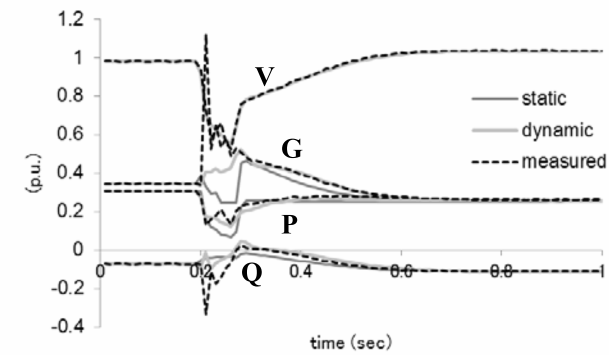

Fig. 2.6 Represented voltage sag by giving voltage

Load parameters
- Static load model
  - α = 0
  - β = 0.5
- Dynamic load model
  - IM ratio　68%
  - IM inertia　0.47sec
  - IM loading　62%

To calculate studied load only, it is a good idea to examine load response by giving measured voltage at the observation point. Results by identified parameters are shown in Fig. 2.6. Since it is not cared that voltage is well represented, load parameter identification becomes possible by realistic labor. Accuracy of dynamic load model is not so improved because its accuracy was already considerably good. On the contrary, accuracy of static load model is considerably improved, because the square form is effectively avoided by giving measured voltage and parameters are chosen so as to minimize the error. Identified load parameters are also shown. In case of static load model, identified parameters are considerably smaller than ordinary values (α = 1 and β = 2), which shows strong constant power character. In calculation here, voltage of observation point that is near to load is given, so ill conversion can be avoided considerably. In case of ordinary power system simulation, voltage sources stand much farther, so ill conversion easily occurs when using such load parameters nearly constant power. Therefore, perhaps it must be the truth that employing nearly constant current static load model to avoid ill conversion, and simulation accuracy is sacrificed. By these problems, engineers adopting static load model cannot have sufficient confidence, and as the result, such useful method as power system simulation has lost credit.

Here before, totally 2 by 2 equal four cases, that is, given fault vs. given voltage, static load model vs. dynamic load model are examined. Total RMS errors of P, Q, and G from 0.27sec (fault clear) to 0.7sec (disturbance end) of the four cases are compared in Fig. 2.7. It is clear that dynamic load model has much better accuracy than static load model.

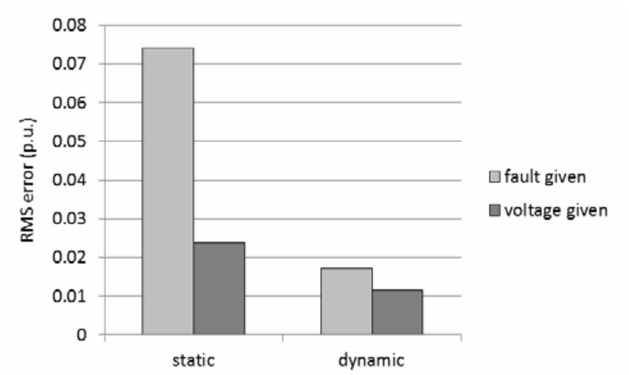

Fig. 2.7 Comparison of representation errors

Identification of System Parameters [7]

Jumping to subject slightly before, two parameters must be identified before load parameter identification. One is impedance from observation point to collective load: Zs, and another is amount of capacitor at observation point: C.

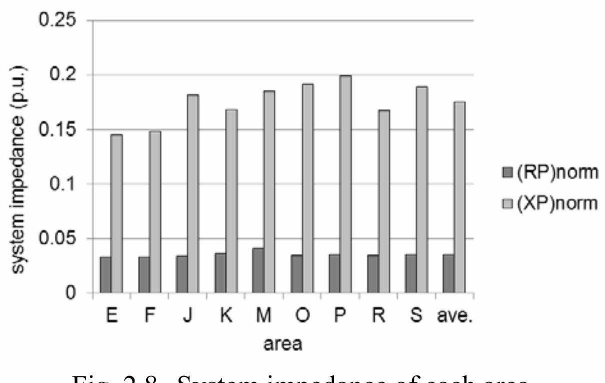

Fig. 2.8 System impedance of each area

Impedance Zs is called as “system impedance” here. In IEEE General Meeting the impedance is called as “feeder equivalent” and the naming sounds suitable. The impedance can be identified by a method called as "aggregation". Since object system is pure load, active and reactive losses due to resistance and reactance should be preserved. Here, nine local pure load systems are examined, and Zs of normal structure at peak demand base are calculated and shown in Fig. 2.8. As an example, expression that $(RP)_{norm}$ is 3% means 3% of active power will be lost at peak load period. System reactance $(XP)_{norm}$ is 6 times larger than system resistance $(RP)_{norm}$.

System impedance at normal structure $(RP)_{norm} + j\,(XP)_{norm}$ is identified. However, power system very often takes temporary structure due to mending work, and so on. System impedance at temporary structure $(RP)_{temp} + j\,(XP)_{temp}$ can be presumed as follows.

$$(RP)_{temp} + j\,(XP)_{temp} = \frac{ALC_{norm}}{ALC_{temp}} \{(RP)_{norm} + j\,(XP)_{norm}\}$$

Here, allocation of demand in whole system is assumed as ALC_{norm} in normal structure and as ALC_{temp} in temporary structure. That is, system impedance is assumed as reverse proportional to demand allocation. The assumption will be realistic if there are no outraged loads.

However, how demand reduced compared with peak demand is different by area. Therefore, demand allocation at peak demand period keeping temporary structure must be presumed. As an example, demand allocation of area J as affected by total demand is shown in Fig. 2.9. Since area J is a typical commercial area demand allocation quite reduces in low demand period such as night. Therefore, some correction is needed so as to make demand allocation of area J at peak demand a little higher. The correction result is also shown in the Figure.

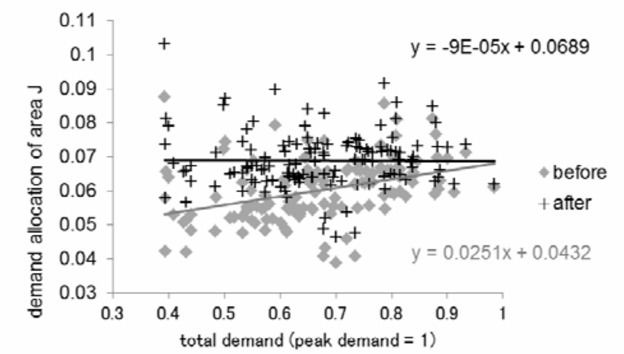

Fig. 2.9 Demand allocation of area J and total demand

Next as to the capacitor amount C, usually observation point is locates at 66kV class bus of primary substation, where considerable le amount of capacitors are equipped, and structure of Fig. 2.3 is realistic. Operations of those capacitors are recorded, but capacitors also exist at 66kV class buses of intermediate substations, 6.6kV buses of distribution substations, buses at consumers, and load terminals. Since capacitors are aggregated at only observation point and load terminal, capacitor amount at observation bus must be set slightly large.

To identify capacitor amount to be set at observation bus, the author focuses to load impedance seen from observation bus as follows.

$$Z = (1/G) + j\,X$$

G and X are calculated as follows.

$$G = \frac{P^2 + (Q + CV^2)^2}{P V^2} \quad 、 \quad X = \frac{(Q + CV^2) V^2}{P^2 + (Q + CV^2)^2}$$

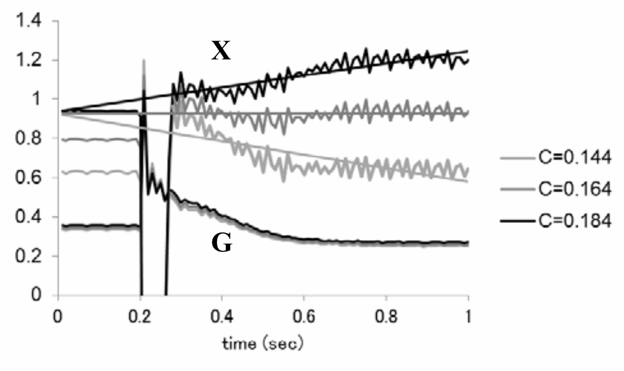

Fig. 2.10 Variation of X and G by C

Here, setting C as adequate value, time sequential variation of X after voltage sag becomes flat as shown in Fig. 2.10. Assuming that only reduction of load's internal resistance is the change due to voltage sag, X certainly becomes flat. (Reality such as IM is slightly more complex.) On the contrary, G is hardly affected by C. It is a relief. G acts an important role for identifying parameters of IM load. Although identification method of C is not so reliable, accuracy of identified IM load parameters will not be spoiled much. Therefore, instead of the method introduced here, it may bring no problems to take capacitor amount at observation bus as C.

Identification of IM Load Parameters (7) (8)

Among various parameters, Inertia Mm, resistances R_1 and R_2, reactances X_1 and X_2 were already investigated about 30 years ago, and reported as Table 2.1 as to 10kW class IM. Hereafter they are adopted. However, only inertia must be added inertia of mechanical load on the shaft. On the contrary, IM inertia may be smaller because of technical advance of the 30 years. Therefore, inertia is identified by measured data here.

Table 2.1 Parameters of IM

Mm	X_1	X_2	Xm	R_1	R_2
0.4sec	0.1	0.1	2.3	0.04	0.04

There are two important parameters to be identified. The first is of course IM ratio Rm, which means percentage of electricity used by IM among all load. The second is IM loading Lm, which means percentage of IM consuming power (kW) against IM rated capacity (kVA). Usually IM is not used at its maximum load.

Various parameter identification methods exist. Here, a primitive but sure method as follows is adopted.

(1) At first, with fixed Lm and Mm, identification error is calculated for some Rm cases. The results can be explained approximately by parabolic curve pointing downward. Thus, minimum error by Rm and

the Rm value giving the minimum error are calculated.

(2) Next, for several combination of assumed Mm, minimum error by Rm, and the Rm value giving the minimum error, approximations are made by parabolic curves pointing downward. Thus, minimum error by Mm and pair of Mm and Rm giving the minimum error are calculated.

(3) At last, for several combination of assumed Lm, minimum error by Mm, and the pair of Mm and Rm giving the minimum error, approximation are made by parabolic curves pointing downward. Thus, minimum error by Lm and combination of Mm, Rm, and Lm giving the minimum error are calculated.

The method is primitive, quite laborious, and morale losing because many calculations are needed for quite apart from values to be identified, therefore, not favorable. However, (even though proved by experiences only) minimum error is surely calculated if it exists, only if interval of assuming loading, inertia, and ratio of IM are adequately set.

Here, it must be noticed that obtained IM ratio Rm is the value after voltage sag. Generally, considerable amount of loads drop if depth of the sag exceeds 20%. Obtained Rm also shows IM ratio after voltage sag, if drop ratio of IM is equal to that of the other loads. However, there is no basis to believe the equal drop ratio. To investigate difference of drop ratios, relations of IM ratio after sag and load drop ratio are plotted in Fig. 2.11. The higher load drop ratio is, the higher IM ratio after voltage sag. The result seems queer. To explain the queer result, a w working hypothesis that “only not IM loads drop due to voltage sag” is employed. According to the hypothesis IM ratio before sag can be presumed. The results are also shown in the Figure. Slope of trend line becomes considerably flat. Therefore, the hypothesis seems adequate.

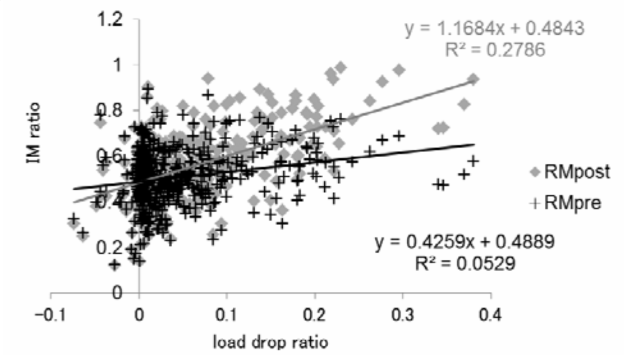

Fig. 2.11 Presuming IM ratio before voltage sag

In truth, most IMs in Japan are protected by motor breaker or delayed disconnecting magnet contactor with thermal relay, both of which do not disconnect due to voltage sag. The working hypothesis above seems adequate from design of equipment.

By the way, load drop ratio becomes higher by deeper voltage sag, and the relation is shown in Fig. 2.12. Load hardly drops by 15.8% depth sag or shallower. Load drop ratio is saturated at 25% by 57.3% depth sag or deeper. The saturated value was around 30% in 20th century. Perhaps, countermeasures such as voltage sag compensator have penetrated.

Thus, all parameters of IM load model are identified. However, observed system is not always pure load but sometimes contains small amount of synchronous generators such as customer-owned generators, which are not able to be supervised by SCADA (Supervisory Telecontrol and Data Acquisition) in central dispatching office. Therefore, it is convenient if pure load behavior is presumed by correcting measured data.

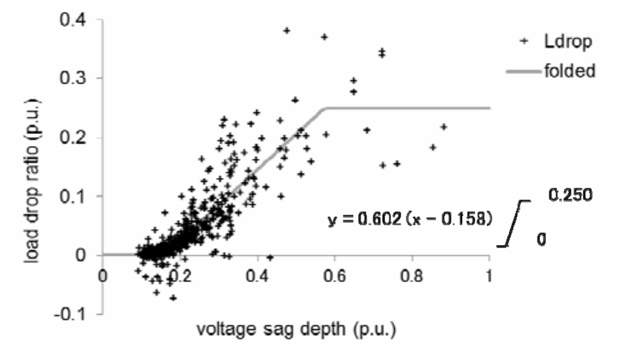

Fig. 2.12 Sag depth and load drop ratio

Here, the author focuses to reactive power supplied by synchronous generator during voltage sag. IM also supplies reactive power during voltage sag, however, the amount is quite smaller than synchronous generator. As the result, reverse reactive power during voltage sag defined as Fig. 2.13 will vary by amount of synchronous generators in the studied load.

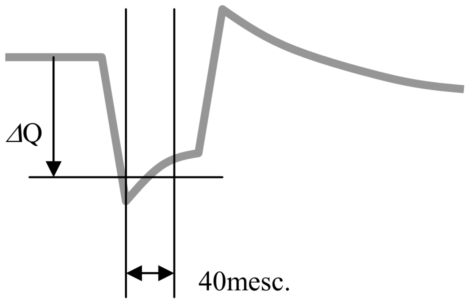

Fig. 2.13 Reactive power behavior and definition of ΔQ

Observed ΔQ is compared to simulation-represented value ΔQ_{sim}. $\Delta Q - \Delta Q_{sim}$ will be larger when sag is depth ΔV (maximum average depth of continuous 40 msec) is larger. Therefore an index Iq that is normalized by active power before sag P_0 and sag depth ΔV is defined and called as "relative reactive power error index". Larger index means much amount of synchronous generators such as customer-owned generators.

$$Iq = \frac{\Delta Q - \Delta Q_{sim}}{P_0 \, \Delta V}$$

IM ratio before sag Rm and IM inertia Mm may somewhat depend on demand before sag Ppre. IM loading Lm surely depends on Ppre. Therefore, it is reasonable to explain the three parameters Rm, Mm, and Lm by both of Ppre and Iq. Employed measure is correlation by multiple variables. Presumed values Rm*, Mm*, and Lm* can be expressed by linear equations as follows.

$$Rm^* = A_R \, Ppre + B_R \, Iq + C_R$$
$$Mm^* = A_M \, Ppre + B_M \, Iq + C_M$$
$$Lm^* = A_L \, Ppre + B_L \, Iq + C_L$$

In the examole case coefficients are calculated as follows. A_L takes a large negative value.

$$A_R = -0.09281, \quad B_R = -0.00784, \quad C_R = 0.575094$$
$$A_M = -0.05433, \quad B_M = 0.063246, \quad C_M = 0.431154$$
$$A_L = -0.45432, \quad B_L = 0.071733, \quad C_L = 0.967485$$

Three parameters Rm', Mm', and Lm' at Iq = 0, which means customer-owned generators and those feeding loads are eliminated, can be presumed as follows.

$$Rm' = Rm - B_R\, Iq$$
$$Mm' = Mm - B_M\, Iq$$
$$Lm' = Lm - B_L\, Iq$$

Thus, IM load parameters before sag of 467 measured data recorded in 1998-2010 are identified, and the results are shown with relation with demand in Fig. 2.14 to 2.16. IM ratio is not affected by demand much, and average value is almost 50%. IM inertia is also not affected by demand much, and average value is around 0.4 sec. IM loading is quite affected by demand, becomes lower when demand is higher, is around 50% at peak demand, and is around 70% at half demand.

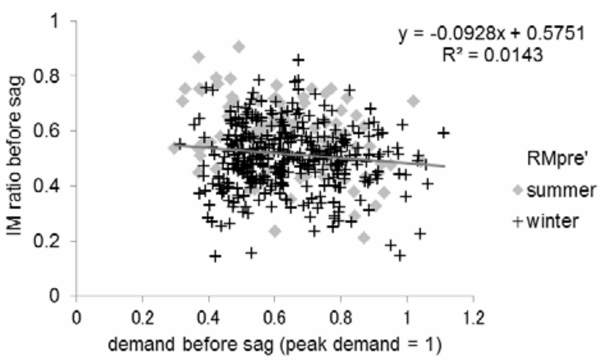

Fig. 2.14 IM ratio before sag and demand

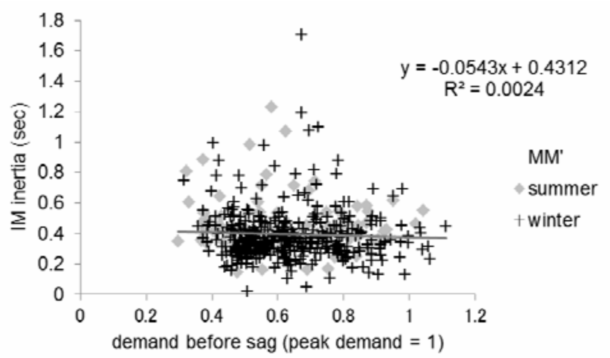

Fig. 2.15 IM inertia and demand

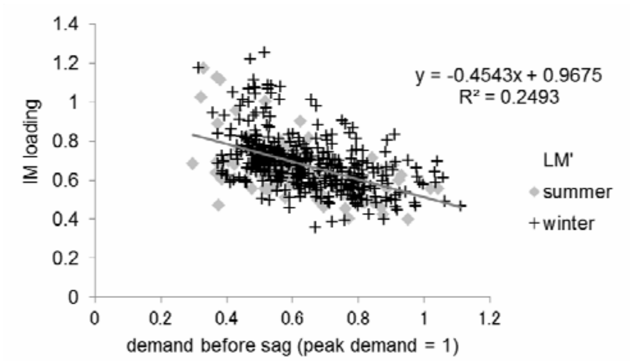

Fig. 2.16 IM loading and demand

The tendency of IM loading can be explained as follows. IM loads during low demand are mainly infrastructure use such as pump and fan. Those IMs are controlled only on/off, and operate almost maximum loading for economy. In higher demand period, industrial machines such as drill and grinder join. Those machines operate almost no load usually and operate temporarily at high loading. As the result, average IM loading becomes lower at higher demand.

Here, some data show higher demand than 1. Some people seem not able to understand. Therefore, the author tries to explain. Peak demand of an area sometimes exceeds the area's demand when total system shows its peak demand. This is so-called "diversity", and is an important factor in electric power system engineering.

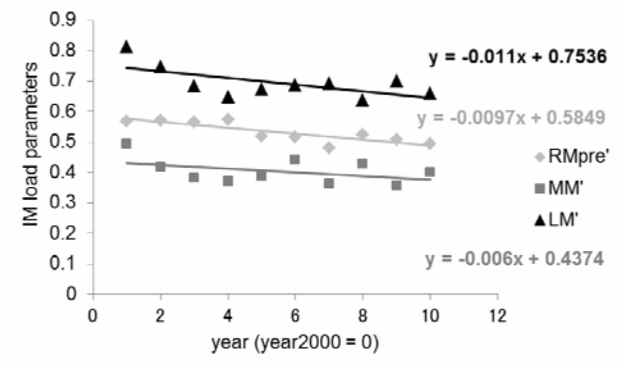

Fig. 2.17 Yearly variation of IM load parameters

Yearly variation of IM ratio, IM inertia, and IM loading are shown in Fig. 2.17. The three parameters slowly decrease by year. It can be not denied that increase of inverter driven IM has brought the results as some people say. However, total capacity of inverter driven IM is not large. By the way, it must be noticed before 2002 that number of observation sites were few, data of considerable number of areas were not included, and as the result identified parameters do not have high reliability. Therefore, measuring and analyzing must be conducted also in near future.

Thus, remainder three parameters of IM load are identified. What about the accuracy? Data scatter in wide area. When identifying the three parameters, expectation of time accumulated square error e_{opt} is also calculated. Simulation results using the identified three parameters are also performed and the expectation error e is also calculated. For identifying the three parameters at least 27 simulations are performed, and least error among them e_{min} is also calculated. Relationship of the three errors must be as follows.

$$e_{opt} \fallingdotseq e < e_{min}$$

Then, two indices as follows are calculated.

$$(e / e_{opt}) - 1 , \quad (e / e_{min}) - 1$$

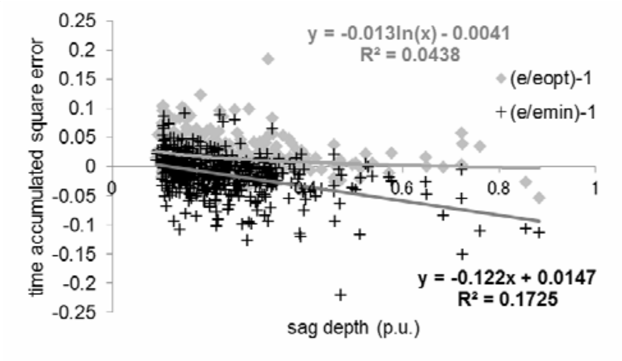

Fig. 2.18 Identification error index and sag depth

Relationship between the two indices above and sag depth is shown in Fig. 2.18. If identification is reliable $(e / e_{opt}) - 1$ must be almost zero. In the Figure, the index becomes nearly zero at deeper sag. Since accuracy is regarded well in deep sag cases, identification here is considered as reliable. If identification is reliable $(e / e_{min}) - 1$ must be slightly more than zero. In the Figure the index takes little negative value at deeper sag. In this point of view, identification here is considered as reliable. Wide scattering does not necessarily mean much error but does mean diversity by day, time, area, and so on.

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