2. Load model

Importance of realistic power system model[1]

Notwithstanding analysis methods (manual calculation or simulation), reliability of analyzed result depends on product of tool's reliability and data's reliability. Since tools are used many scientists, defects are corrected soon and their reliability is well verified. However, models are different by objects or scientists, and their reliability is not well verified. Therefore, it is mainly not tools but models that spoil reliability of analysis.

Studying impacts of renewable energy (RE) on power system, RE model and power system model are employed. Since RE model is verified by test using real equipment, accurate model can be built. On the contrary, since test on real power system is avoided for avoiding customers' nuisance, verification of power system model is difficult. Therefore, it is not RE model but power system model that spoils reliability of assessing RE's impact on power system. For verifying power system model, it is indispensable to reproduce recorded unfavorable physical phenomena, and of course, to faithfully model machines and equipment.

Power system analysis became efficient by simulation tools and almost established in 1970Ss. In IEEJ journal Jan. 1980, a special issue is published, and in its chapter "power system stability analysis[2]", four items as follows were referred as necessary researches in near future.

1) Accurate data acquisition and efficient data management system.
2) Easy measurement methods for generator and control systems.
3) Investigation of existing loads and adequate load modeling
4) Accurate system aggregation method.

Accurate data acquisition and relating items are matter of course. Necessary theoretical progresses were regarded as the two: load model and system aggregation. However up to 2017, generally very poor progress is seen in the two fields in Japan. Therefore before studying RE impacts on power system, two chapters are set in the book, and introduced but not penetrated progress in the two fields are discussed. Of course the purpose is to use in the later chapters.

History of load model

Static load model In early stage of power system analysis load was not modeled but by resistance. However, it was noticed that load's voltage and frequency sensitivities affect to stability. When generator is accelerating, by load's positive voltage sensitivity sending power flow increases, load voltage decreases, load's consumption power decreases, thus sending power increases further, and stability is spoiled. When frequency is increasing, by load's positive frequency sensitivity load's consumption power increases, frequency rise is mitigated, thus power swing is damped, and stability is improved.

What suits the purpose is static load model. In US, load is expresses by mixture of constant impedance (CZ), constant current (CI), and constant power (CP), which is called as ZIP load. In Japan, load is expresses by index function as follows.

$$P = P_0 (V/V_0)^{\alpha} (f/f_0)^{\gamma}, \quad Q = Q_0 (V/V_0)^{\beta} (f/f_0)^{\delta} \qquad (2.1)$$

Indexes $\alpha = 1$, $\beta = 2$, $\gamma = 2$, $\delta = 0$ derived from slow and small disturbance are generally used. If induction motor as CP and CZ are mixed half and half, total index becomes 1. Mechanical torque such as pump is proportional to square speed and is main source of positive frequency sensitivity.

In these load model, load's active and reactive power is decided only by the present voltage and frequency, is never affected by past history (this is a quite queer character), and is expressed by algebraic equation, so called as "static load model".

Since static load model was derived from slow and small disturbance, its reliability is doubtful in fast and large disturbance. Network fault is the typical. Using static load model, ill convergence often occurs in simulation. As the countermeasure, load is changed as CZ during low voltage (70% in general). Also voltage returning to original character is set as 80% for avoiding hunting. Thud most ill convergence is cleared. However, "change to CZ" is a conventional method for avoiding stop of calculation. Existing load does not changes to CZ. In later era, expression such as "it is known that load changes to CZ when voltage decreases[3]" is seen in article. However by measurement, load is not CZ but its conductance increases during low voltage.

Dynamic load model In the end of 20th century, limitation of static load model was noticed, and dynamic load model was researched mainly in US. There were two methodologies.

The first is called as *Coherency Based*, which makes up load model as mixture of existing electric equipment and has a merit that physical phenomena are preserved. However, the mixed ratio will varies by season, time, high/low demand, region. It is difficult to presume the mixed ratio from limited number of sampled data.

The second is called as *Measurement Based*, which expresses load model by *a priori* assumed function, and has a merit that parameters of the function are identified by measured data. However, most measured data are acquired from small disturbance, and orthodoxy of *a priori* assumed function.

Long fruitless controversy had been held between the two parties. Ref. (5) and (6) are typical *Measurement Based* papers. Discussions were made from *Component Based* party. Volume of discussion sometimes exceeds volume of the paper itself. The discussions show the difference of the two methods and confusion in those days.

Discussers 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 nature of existing loads, and if unknown parameters of the model can be identified by measured data". Earlier than hoped, the third party appeared at the end of 20th century. Ref. (7) and (8) are the pioneers. By the *aufheben*, controversy between the two parties was dissolute.

In the same era in Japan, it is pointed out that load's internal conductance G must be taken as variable instead of power, P and Q, which are inadequate for variable because they are decided by the other variables and parameters. The thought is same as the third party.

Progress of measurement system Front half of the third party's opinion "if a certain mathematical model can represent physical structure and nature of existing loads" was realized by *Component Based* method including induction motor. Rear half of it "if unknown parameters of the model can be identified by measured data" is *Measurement Based* method itself and was realized by progress of measurement system.

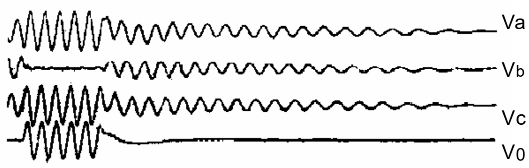

Fig 2.1 Record of transmission line failure by Carpentier

Until 1970s, only analogue oscillograph that is called by inventor's name "Carpentier" was used in measurement. Ref. (10) presents two evidences showing existence induction motor load. One is Carpentier record shown in Fig. 2.1. This is the record when outage occurred in a 154kV substation by shutdown of 154kV 2-circuit transmission line feeding the substation due to grounding fault. Voltage waves of 60Hz every phase and zero sequence are recorded. During a short time voltages decrease but continue. The phenomenon indicates that induction motor load turns to induction generator, and is a powerful circumstantial evidence that much amount of induction motor exist in load.

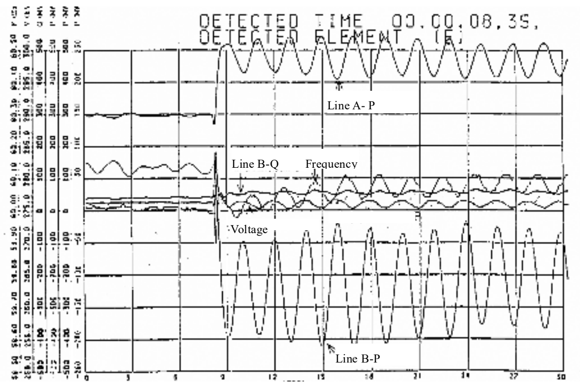

Fig. 2.2 Record of power swing by PQVF

In 1980s a measurement system called "PQVF" that records power: P, Q, voltage: V, and frequency: F mainly for power swing was introduced. A typical power swing record is shown in Fig. 2,2(1).

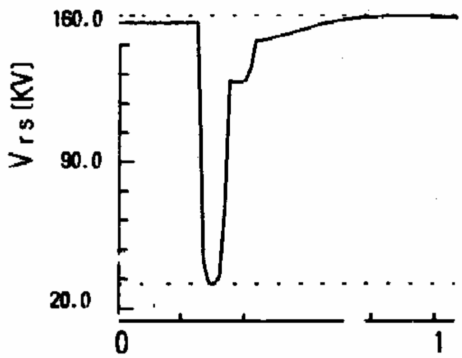

Fig. 2.3 Record of voltage sag by PQVF

"PQVF" is convenient because digital values are given, however, sampling time is 0.1 sec, which is far longer for voltage sag recording. The second evidence showing existence of induction motor load by Ref. (10) is shown in Fig. 2.3. This is the record of 154kV bus voltage sag caused by 1-circuit 3LG-O fault double circuit transmission line. Failure is cleared by 0.1sec, but more 0.1 sec is needed for recovering to normal. The phenomenon indicates that internal resistance of induction motor load decreases during fault.

At the end of 20th century, digital oscillograph called such as "multi-functional oscillograph" appeared. Sampling time of the txample here is 1/3840 sec for 60Hz usage.

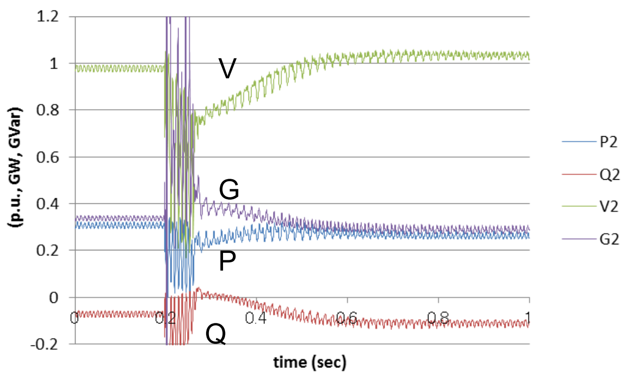

Fig 2.4 Record by digital oscillograph (αβ transform)

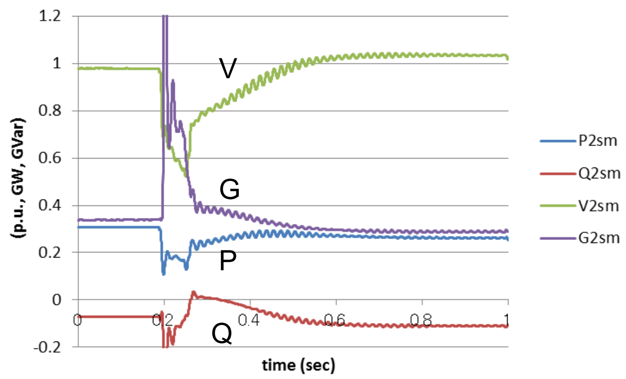

Fig. 2.5 Record by digital osc. (half wave moving average)

Three-phase instance value of voltage and current are recorded. They are αβ transformed to r.m.s. values as shown in Fig. 2.4. It is cause by two-phase failure, so includes fast component by negative sequence component during fault, and the component still remains after fault clear. For putting away the component half wave moving average of 60Hz is taken. As the result, Fig. 2.5 is obtained, in which clear figures and digital values are drawn and time delay is not much.

Establishment of dynamic load model According to progress of measurement system, EPRI of US started a project in 2005 to build up dynamic load model through voltage sag measurement(11). Because, it is voltage sag that can be recorded many specimens of large disturbance. Although Japan neither joined it nor started similar project, a party started to establish dynamic load model(4).

Then, it is indispensable to model a bus-to-load aggregated impedance that certainly exists in network, instead of connecting load directly to bus, for reproducing existing phenomena. The impedance is called as "load branch" in 2006 Japanese paper(4) and is called as "feeder equivalent" in 2008 US report(12). By employing load branch the "fault induced delayed voltage recovery (FIDVR)" can be reproduced accurately. "Load branch" theory is reliable, because independent two researches reaches the same conclusion in Japan and US. "Load branch" impedance from 66kV class bus to load terminal is around 3.5 + j17.5% at peak demand base in Japan.

Dynamic load model is once established in Ref. (13) and (14). Dynamic load model is nowadays takes structure shown in Fig. 2.6. Paralleled induction motor, resistor, and capacitor are connected to observation bus at substation via "load branch" impedance. However, the model is not new one. Already Ref. (2) in 1980 recognized that "by modeling a part of load as induction motor, power system stability analysis considering 'load's dynamic behavior against voltage and frequency variation' that was not realized by expression as function". Ref. (13) and (14) can be said that they showed small improvement in reproduction accuracy by introducing "load branch" into Ref. (2). Japanese electric engineers must apologize much around poor progress in load model after 1980.

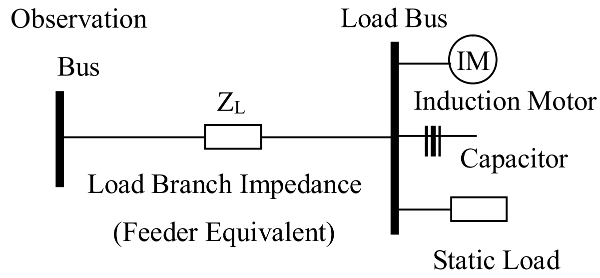

図 2.6 近代的な動的負荷モデルの構造

Progress in parameter identification

Reduction of reproduction error Although policy of building dynamic load model by employing induction motor load and load branch is concreted, unknown parameters must be identified through measurement. Constants of induction motor do not scatter widely and some reports exist. Among them, average inertia is reported as 0.4 sec, but can increase by mechanical load, so must be identified. In addition, motor ratio (motor consumption power kW/load consumption power kW) and motor loading (motor consumption power kW/motor capacity kVA) must be identified. Also is needed load branch impedance, which can be calculated by power system aggregation. Thus, the three: motor ratio, inertia, and loading must be identified through measured data.

In the beginning of the research, the author took it of course that load's behavior should reproduced by fiving some fault (2LG-3LO for example). An example is shown in Fig. 2.6. Here, G is load's internal conductance when load is regarded as variable conductance behind fixed reactance. Voltage V once recovers to 80% or less, but recovery thereafter is slow. Reactive power Q temporary increases just after fault clear. These phenomena are caused by induction motor, and is seen every voltage sag. Dynamic load model can reproduce the tendency well. The reason why measurement and reproduction do not agree perfectly is impact by the other loads.

On the contrary static load model shows square form in V, Q, and P that jump to destination value just at fault clear timing. That is far different measured fact. Most technical reports in Japan express voltage profile in voltage sag as these square form. Engineers must not believe it as the truth.

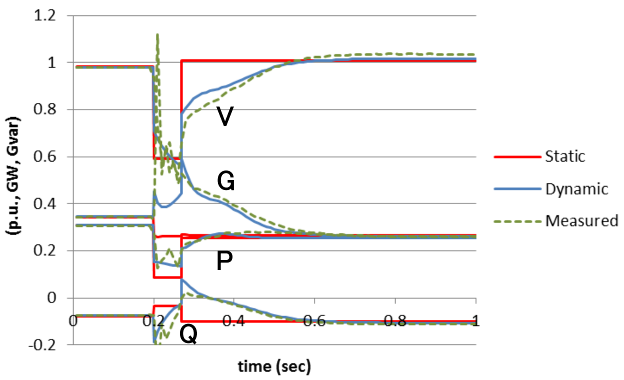

Fig. 2.6 Reproduced load's behavir by giving fault

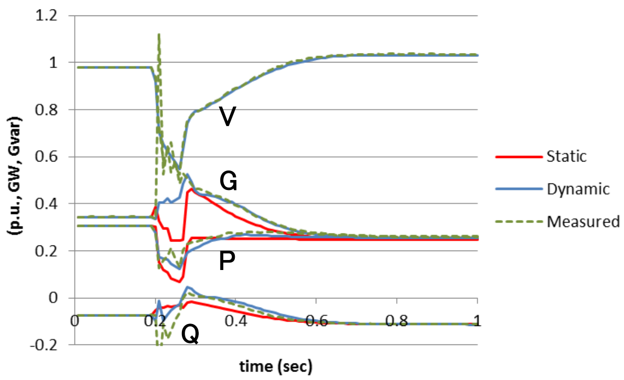

Fig. 2.7 Reproduced load' behavior by giving voltage

It is quite difficult to adjust the four simulated variable P, Q, V, and G to Measured records. As a solution measured voltage is given. An example is shown in Fig. 2.7. By the measure, impact by the other loads is excluded. Dynamic load model can reproduce reality up to piling up the simulated on the measured.

In case of static load, voltage profile is far different from the given voltage. Therefore, study in Fig. 2.7 may be meaningless, but the simulated somewhat disagree with the simulated.

Resistance of load branch[14] In early stage of the research, the author modeled load branch as pure reactance, because resistance of distribution network is unknown. Afterwards, aggregation of distribution networks were performed and it was concluded that aggregation impedance of distribution networks is around 3 + j6% at peak demand base. Load branch impedance including distribution network impedance is not much different by area as sown in Fig. 2.8, and average is 3.5 + j17.5% at peak demand base.

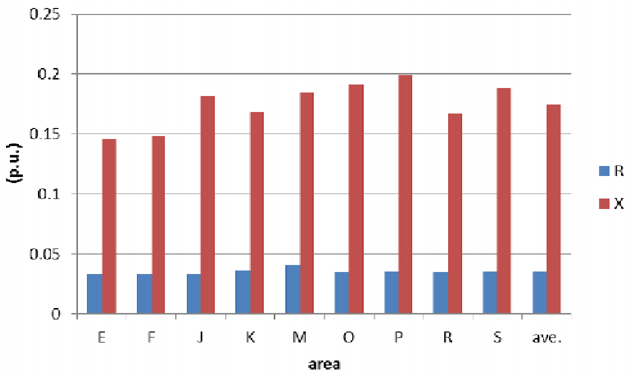

Fig. 2.8 Load branch impedance by area

Accuracy improvement of given voltage[15] What is recorded in digital oscillograph is three phase instant value of voltage and current. Since simulation tool operate as r.m.s. value, recorded instant values must be transformed to r.m.s. values. The author's first transforming method divides record into blocks of every 38 or 39 data from the beginning of 1/3840 sec digital data, and takes average of every block for feeding simulation tool at Fig. 2.4 condition. As the result, sharpness of voltage drop was somewhat lost. Also, reduction of negative sequence component was not sufficient.

Improved transforming method select one data from every 38 to 39 data for representing 10msec time section by making the start point of voltage drop as reference timing for the selection in Fig. 2.5 condition. Difference of the two methods is shown in Fig. 2.9. Lag of voltage profile is seen in old method but hardly seen in new method as compared voltage profile before sampling by 10msec shown in Fig. 2.4.

Difference in given voltage will result difference in parameter identification results. So, both methods are applied to common 347 data. Identified parameters (motor ratio RM, inertia MM, and loading LM) are compared in Fig. 2.10. All the three parameters by new method are slightly larger than those by old method, but the difference is small. The reason is that motor's behavior after sag is much ruled by deccereration during fault, and the decceralation ruled more by product of depth and duration of sag than bay voltage profile itself.

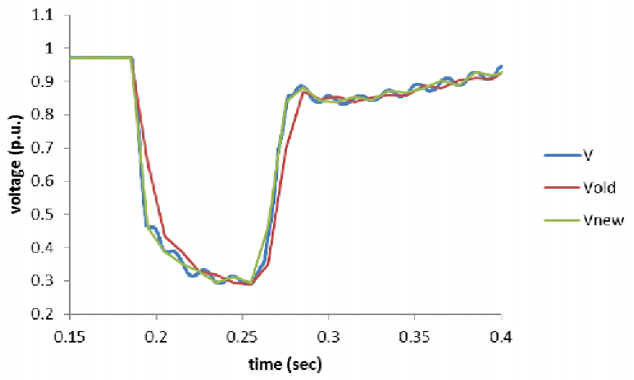

Fig. 2.9 Improvement in voltage profile

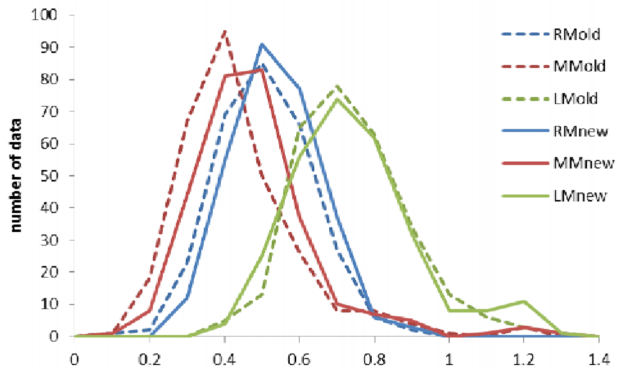

Fig. 2.10 Impact of voltage profile on parameter identification

Avoiding ill identification(15) More serious problem is that there were many cases that identification was not achieved successfully by old method especially in shallow sag cases. That means not only decrease of contribution by data but also spoiling reliability of identification method.

When identifying motor ratio RM, inertia MM, and loading LM by old method, first a LM is assumed and MMopt and RMopt pair giving least error is identified on MM – RM plane. In the stage accident that RM was not identified within 0 to 1 value often occurred.

Dynamid behavior of induction motor appears stronger when RM is larger. Also when MM is smaller, appears fasterans stronger. In minimizing error, large MM and small MM have a trade-off relationship, and small error zone appears slanting in MM – RM plane as shown in Fig. 2.11. Since factors that increase error at both end (0 and 1) of RM are weak, identifivation in the zone becomes difficult.

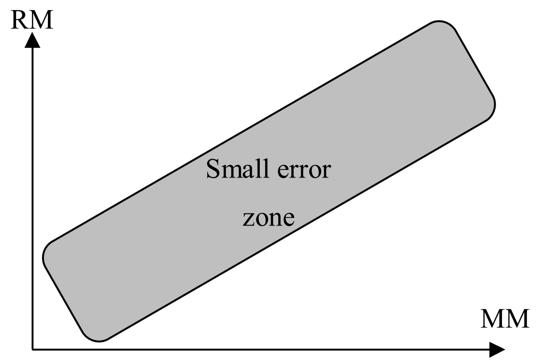

Fig. 2.11 Small error zone in MM-RM plane

As a countermeasure, order of identification is changed in new method. First assumiing some MM, and Lmoptand Rmopt pair giving minimum error is identified on LM – RM plane. By the improvement impossible identification case vanished away.

Considering the fact, when LM is small, motor capacity is large and dynamic behavior due to magnetic flux variation strongly appears. On the contrary when LM is large, slip of motor is large and dynamic behavior due to deccerelation strongly appears. Thus at the edge of small and large LM error becomes large, and parameters LM and RM are well identified in middle LM zone.

Using the 565 case voltage sag data measured until 2010, parameters are identified by both old and new methods. Number of successful identification, average sag depth, and its standard deviation are shown in Table 2.1. number of success by old method is 347, which is only 61% of total 565 cases. All 565 cases were

Table 2.1 Number of identified cases and sag depth

	old	new only	new
N	347	218	565
m	0.232606	0.118631	0.19075
σ	0.124679	0.067341	0.120767

successfully identified by new method. 218 cases are identified only by new method. Average sag depth identified by old method is deep as 23%, and that being identified only by new method is shallow as 12%. In addition, histgram of successful identification by sag depth is shown in Fig. 2.12. Certainly it is noticed that number of cases identified by only new method is large at shallow sag region.

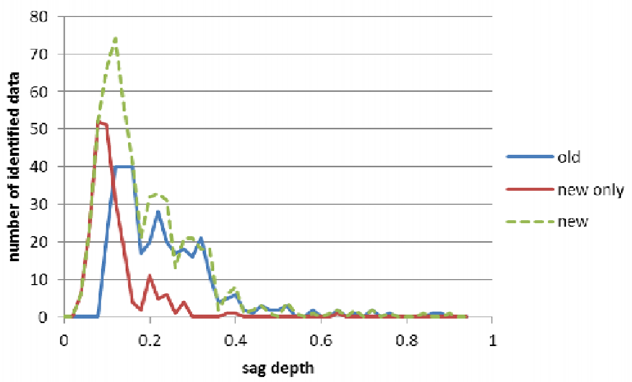

Fig. 2.12 Number of identified cases by sag depth

Identified parameters[15]

Partial load drop due to voltage sag In Fig. 2.8 parameters of nine area that can be regarded as pure load system. However, area E often includes considerable hydro generation by temporary structure. Area F and S turn to a part of area M and R in later years. Excluding these three areas, six areas remain as pure load system. Number of voltage sag data in the six area is 974 till 2014fy. In all cases parameters are successfully identified by new method.

At first, partial load drop ratio by sag depth is shown in Fig. 2.13. It must be noticed that negative load drop ratiois observed in shallow sag depth, 22% or less. Negative load drop was not observed in the first report[13] on 2007 or before, and is thought by impact of RE penetration. Considerable amount of wind power penetrated in area M. Most of them do not prepare FRT capability and stop by only 10% voltage sag. Load does not drop by such shallow sag.

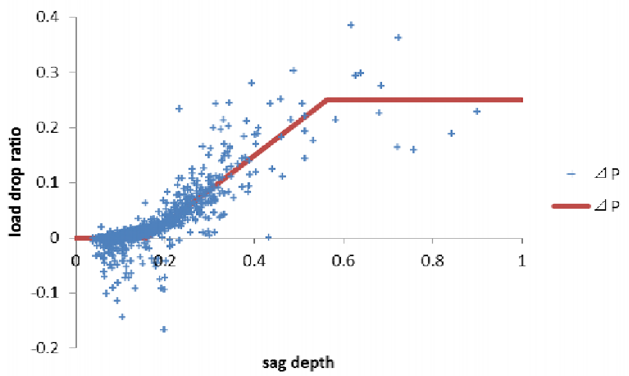

Fig. 2.13 Load drop ratio by sag depth

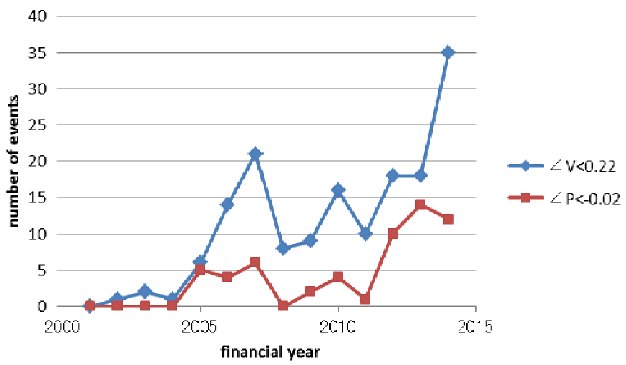

Fig. 2.14 Yearly trend of negative load drop ratio

By further examination, negative load drop of -0.02 or under were observed 1 in area K, 58 in area M, and 1 in area P. Among them, 2 of area K and P are very slight as not reaching -0.03. Therefore, most negative load drop are observed in area M. This is not independent from the fact that considerable amount of wind power is integrated in area M.

In Fig. 2.14, yearly number of sag with 22% depth or shallower and number of negative load drop events are shown. Number of negative load drop events increases in 2007 or after significantly. The fact that negative load drop events are still observed in 2014 tells that effective FRT function is not employed in wind power yet. In 2014, events of negative load drop is not so large compared to number of shallow voltage sag. The fact nay indicate that FRT function gradually penetrates into wind power. However, the tendency is observed only in one year. Continuous observation is needed toward near future.

Estimation of motor ratio before sag It is not motor ratio before sag but that after sag that is identified. In general, motor ratio before sag is not always equal to that after sag. It must be clarified which, motor or the others, mainly drops due to voltage sag. Relationship between load drop ratio and motor ratio after sag is shown in Fig. 2.15[15].

The figure tells that motor ratio is higher when load drop ratio is higher. It seems quite unnatural that motor ratio is strongly dependent to load drop ratio. Here, a hypothesis "motors never stop but the other loads stop due to sag" is introduced. Employing the hypothesis, motor ratio before sag can be estimated. The results are also shown in the figure. Slope of trend line becomes smaller by the hypothesis, that is sag depth and motor ratio before sag are almost independent. Thus, the hypothesis is thought as true. The hypothesis agrees with the fast that induction motors in Japan are mainly protected by motor breaker or magnet contactor with delayed breaking, and as the result, tend not to stop due to voltage sag.

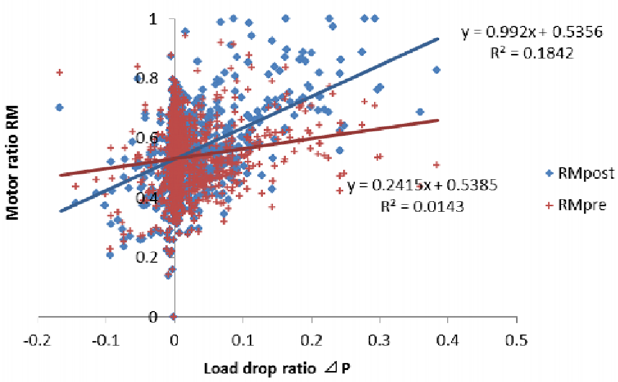

図 2.15 負荷停止率と誘導機比率の関係

Identified the three parameters Histogram of the identified three parameters are shown in Fig. 2.16 by 0.1 p.u. division. Tendency is not changed from Fig. 2.10 up to 2010.

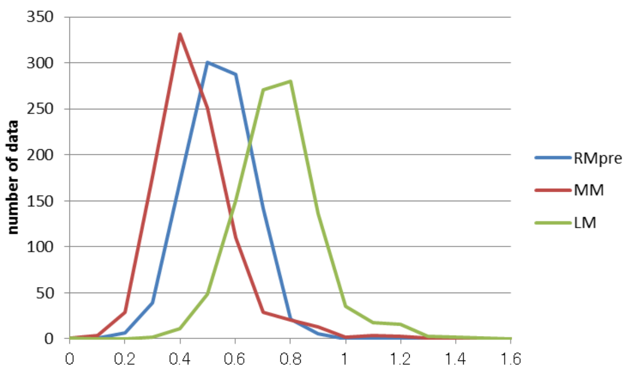

Fig. 2.16 Histogram of the three parameters

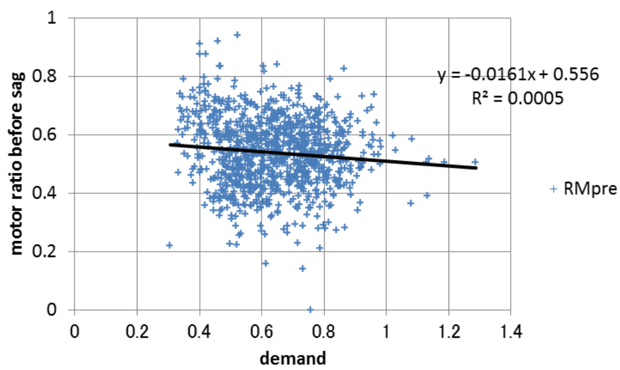

Fig. 2.17 Motor ratio before sag by demand

Relationship between motor ratio before sag and demand are plotted as Fig. 2.17. Motor ratio is around 50% and almost independent from demand. In the figure, some demand over 1 are seen. 1.1 or smaller values can appear due to diversity. Values around 1.2 are explained that area at which sag occurred was larger than area at which demand was recorded at o'clock just by temporary structure. In practical use, demand over 1 is regarded as 1.

Relationship between motor inertia and demand are plotted as Fig. 2,18. Motor inertia is around 0.5 sec and almost independent from demand.

Relationship between motor loading and demand are plotted as Fig. 2.19. On the contrary of ratio and inertia, there is clear negative correlation. Motor loading is low as 0.5 at high demand and is high as 0.8 at low demand. The tendency is explained as follows. In low demand period motors mainly in infrastructure such as pump operate almost at their rated power (high loading). In high demand period join industrial motors such as drill and grinder that almost operate at idle spinning (low loading).

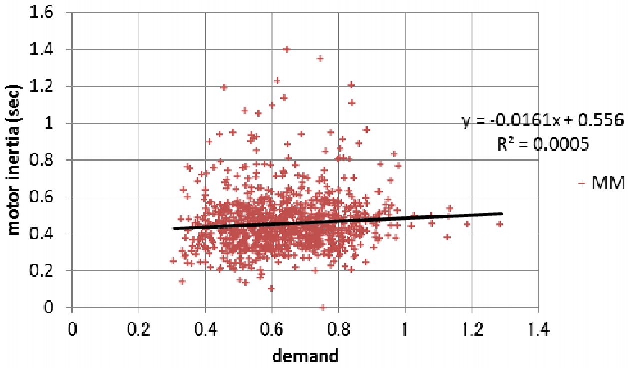

Fig. 2.18 Motor inertia by demand

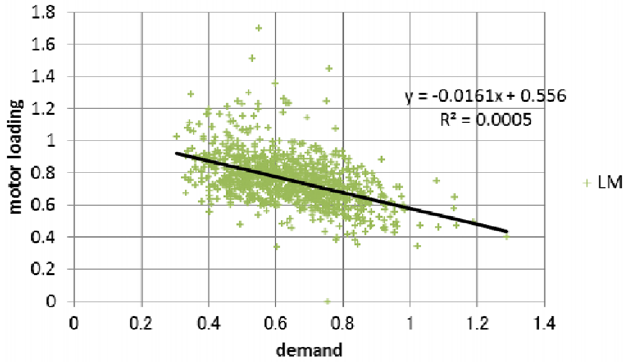

Fig. 2.17 Motor loading by demand

Yearly trend of the three parameters is shown in Fig. 2.18. All of the three parameters slightly decline by year. It is believed that main reason of declining motor ratio is increase of inverter controlled motor. That is perhaps right, but its speed is not fast as believed. The reason is that inverter control is adopted in sophisticated usage such as fine processing, where small motors are mainly used, and inverter controlled motor amount is small at kW base.

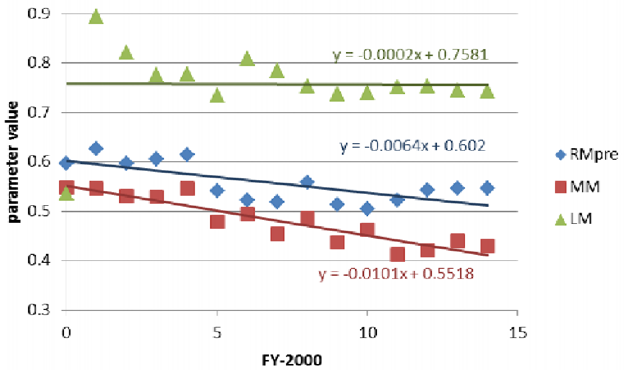

Fig. 2.20 Yearly trend of the three parameters

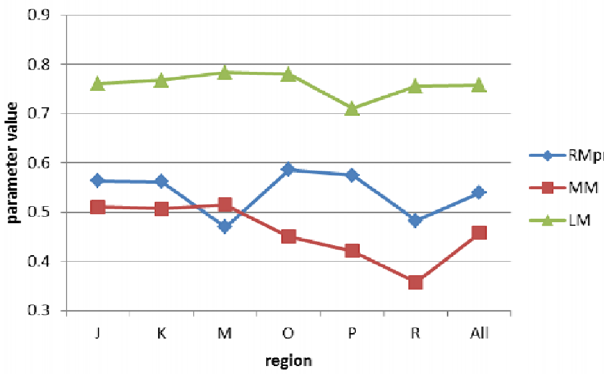

Fig. 2.21 The three parameters by area

Difference of the three parameters by area is shown in Fig. 2.21. Motor ratio before sag RMpre is slightly smaller in area M and R. Inertia MM is slightly smaller in area R. Loading LM is slightly smaller in area P. However difference by area is not large. Parameters in area M where RE highly penetrates are not much different from the other areas.

According to the result above, as induction motor load's parameters for power system analysis, 50% motor ratio before sag, 0.5 sec motor inertia, and 50% motor loading for high demand period or 80% motor loading for low demand are suitable.

Aside from the author's voltage sag observation, motor ratio including inverter controlled is estimated by customers' loads examination and reported as 57% by private section(16) and 55% by Japan government section(17). Results of those three sections well agree. Dynamic load model is almost established. However different from the other countries, dynamic load model is not generally used in daily practice of power system analysis.

Beside electric utilities, Japan government employed top-runner method on efficiency improvement of induction motors(18), following Europe and US, because of the examined result that a large part of electric energy is used by induction motor.

Toward Impact assessment by RE on power system

Different from most developed and developing countries, only Japan continues until now to use static load model built in the former century. By power system model using static load model, screening of impact by RE on power system is impossible.

The first reason is that photovoltaic generation (PV) that amounts considerable part of RE interconnects to power system via inverter, which is constant current source, and is inferior in ability of maintaining power system voltage to conventional synchronous generator, which can be regarded as constant voltage source with internal reactance. In wind power, inverter connected type is adopted and has the same problem. Further, controllability of DFIG (doubly fed induction generator) that is mainly used in wind power is inferior to inverter. Problem is more serious in wind power than in PV.

The second reason is that adopting induction motor load and load branch is unavoidable if power system is realistically modeled. As the result, unstable phenomenon that has been ignored, that is, stall of induction motor cannot kept neglected.

Considering these two major change, it must be minutely examined how analysis results change from those believed. However, although countermeasures for high RE penetration are discussed in many sections, researches paying attention to adequate power system modeling are very few in transactions and none in government committees. The author feel danger in the condition that policy making on high RE integration is entrusted to “so called” experts.

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