Procedure for selection of the SPD system according to the probability of damage

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***Abstract*—In the present paper practical recommendations and procedures are proposed for selection of an SPD system with aim to protect, with a given probability, electronic and electrical apparatus within a structure against overvoltages coming from different sources of damage as defined by IEC 62305 [1]. The investigations are based on several computer simulations, by means of commercial transient software EMTP-RV, at the typical basic arrangement consisting of an apparatus within a structure influenced by direct flashes to the structure (source of damage S1), flashes to ground nearby the structure (source of damage S2), flashes to power and communication lines connected to the structure due to flashes to and near the lines (sources of damage S3 and S4). This work is executed in focus on the frame of discussion on recommendation of IEC/EN 62305 [1] for the selection of coordinated SPD system able to reduce the failure of the apparatus with a given probability.**

Keywords—Apprratus safety; Lightning protection; Overvoltage protection; Surge Protective Device

I. Introduction

Coordinated system of surge protective device (SPD) is the typical protection measure for protection of electrical and electronic systems within a structure against surge due to lightning, taking into account that their failure can be caused by surges arising from different sources of damage [1], namely: direct flashes to the structure (source of damage S1), flashes to ground nearby the structure (source of damage S2), flashes to power and communication lines connected to the structure due to flashes to and near the lines (sources of damage S3 and S4).

An apparatus cannot declared protected against surges caused by lightning without specifying the probability with which it is protected.

For practical applications, the probability of the SPD system to reduce the frequency of damage of apparatus to be protected, is a key point for their proper selection and installations.

Evaluation of probability of a given SPD system to protect the apparatus, or on turn, to select an SPD system able to protect apparatus with a given probability, is a complicated matter because probability P_{SPD} depends on the rated current I_n and I_{imp} of SPD in front of the expected current I_{exp} (and the related charge Q_{exp}) at the SPD installation point. As I_{exp} (and Q_{exp}) changes with the source of damage, the probability P_{SPD} of a SPD system changes with the source of damage.

Ultimately, in dependence on the source of damage, the probability P_{SPD}, that an apparatus protected by an SPD system is damaged, not only depends on the characteristics of the SPD system but also on the characteristics of the upstream line and on those of the downstream protected circuit.

In the previous contributions [2, 3, 4], the expected current I_{exp} (and the related charge Q_{exp}) for typical SPD system have been assessed, according to typical characteristics of the upstream line and of the downstream protected circuit. For this reason several computer simulations by means of commercial transient software EMTP-RV have been executed. The simulations problems have been carefully studied [5-11].

Analysis were performed on the base of computer simulations with models coherent with the real circuits tested in the high voltage laboratory of University of Rome “La Sapienza” and Warsaw University of Technology.

Aim of this paper is to give the requirements and a procedure for selection of a coordinated SPD system able to reduce with a given probability P_{SPD} the frequency of damage of the protected apparatus.

II. Types of SPD System

Three cases of SPD systems can be considered:

1) SPD system type S/L – Consists of only one SPD1, switching or limiting type SPD;

2) SPD system type SL – Consists of SPD1 switching type + SPD2 limiting type;

3) SPD system type LL– Consists of SPD1 limiting type + SPD2 limiting type.

The types of SPD system that can be used depend on the source of damage against which protection is required; in particular:

− Type L SPD system is suitable for sources S2, and S4, but it can also be used for source S3 in some cases;

− Type SL or type LL SPD system is to be used for sources S1 and, in many cases, for source of damage S3.

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III. FAILURE OF APPARATUS PROTECTED BY AN SPD SYSTEM

Failure of an apparatus protected by an SPD system occur either the following conditions occur:

− condition a): The energy related to current I_{SPD} flowing in the point of installation is exceeding the value tolerated by the SPD;

− condition b): The voltage U_{SPD} across SPD when the current I_{SPD} is discharged is exceeding the required protection level U_{pr} of SPD;

As a first approximation, condition a) will occur if the charge Q_{SPD} associated to I_{SPD} exceeds the tolerable one by the SPD.

Condition a) should be verified with reference to the positive strokes, which represent the more severe case, as demonstrated in [12].

Condition b) will occur if the value of U_{SPD} of the SPD exceeds the protection level U_{pr}, required to limit the voltage U_l at the terminals of the apparatus to be protected at values not higher than its rated impulse withstand voltage U_w.

Condition b) should be verified with reference to the subsequent strokes of negative flashes, which represent the most severe case [12].

IV. REQUIREMENTS FOR SPD

A. *Energy withstand requirements of an SPD*

In order to protect an apparatus, an SPD must first be able to withstand the energy related to current I_{SPD} expected at its installation point.

The charge for unit of current associated to the standard current 10/350 µs is Q_{imp} = 0,5 C/kA and the one associated to the standard current 8/20 µs is Q_n = 0,027 C/kA; therefore the SPD will withstand the energy Q_{SPD} related to current I_{SPD} if:

− for SPD tested with I_{imp} (class I test)

$$Q_{SPD} \leq Q_{imp} = I_{imp} / 2 \qquad (1)$$

− for SPD tested with I_n (class II test)

$$Q_{SPD} \leq Q_{max} = I_{max} / 37 \approx I_n / 18{,}5 \qquad (2)$$

at assumption that typically $I_{max} = 2 \times I_n$.

It must be noted than in IEC 61643-11, I_{max} is no longer a mandatory value for class II test SPDs. If I_{max} is declared the protective level at I_{max} should be given that is generally much higher than U_p. This is why coordination tests between SPDs not only cover the sharing of energy between two SPDs but also are checking that protective level at SPD2 is not exceeded when injected current is lower than what SPD1 can withstand. Even if not declared in data sheets, in practice I_{max} is equal to 2 to 3 times I_n. The following assumption has been used for this study : $I_{max} = 2 \times I_n$.

The use of SPDs depends on their withstand capability, classified in IEC 61643-11 for power [13], and in IEC 61643-21 for telecommunication systems.

B. *Voltage limiting performance of an SPD*

The second essential factor for an SPD in order to protect an apparatus, is its voltage limiting performance: the value of U_{SPD} related to current I_{SPD} expected at its installation point should not exceed the protection level U_{pr} of the SPD, required to limit the voltage U_l at the terminals of the apparatus to be protected at values not higher than its rated impulse withstand voltage U_w:

$$U_{SPD} \leq U_{pr} \qquad (3)$$

In determining the protection level U_{pr} of the SPD is necessary to take account of:

- the inductive voltage drop ΔU on the leads/connections of the SPD,

- the effects of surge travelling along the protected circuit,

- the overvoltage U_i induced by lightning current in the protected circuit.

1) Voltage drop ΔU on the connections of an SPD:

When an SPD is connected to equipment to be protected, the inductive voltage drop ΔU of the connecting conductors will affect the effective protection level $U_{P/F}$ of the SPD. The resulting effective protection level $U_{P/F}$, defined as the voltage at the output of the SPD resulting from the protection level and the wiring voltage drop in the leads/connections can be assumed as being [13-14]:

$$U_{P/F} = U_p + \Delta U \quad \text{for voltage limiting type SPD(s)} \qquad (4)$$

$$U_{P/F} = \max(U_p , \Delta U) \quad \text{for voltage switching type SPD(s)} \qquad (5)$$

2) Effects of surge travelling along the protected circuit

During the operating state of an SPD, the voltage between the SPD terminals is limited to $U_{P/F}$ at the location of the SPD. If the length of the circuit between the SPD and the equipment is too long, propagation of surges can lead to an oscillation phenomenon. In the case of an open-circuit at the equipment's terminals, this can increase the overvoltage up to $2U_{P/F}$ and failure of equipment may result even if $U_{P/F} \leq U_W$.

3) Overvoltage U_i induced by lightning current in the protected circuit

Lightning flashes to the structure or to ground nearby the structure can induce an overvoltage U_i in the circuit loop between the SPD and the equipment, which adds to $U_{P/F}$ and thereby reduces the protection efficiency of the SPD. Induced overvoltages increase with the dimensions of the loop (line routing: length of circuit, distance between PE and active conductors) and decrease with attenuation of the magnetic field strength (spatial shielding and/or line shielding) and with increasing distance of induced loop from inducing current.

For evaluation of induced overvoltages U_i, approximate methods can be applied, as reported in [3]. If spatial shielding of the structure (or of the rooms) and/or line shielding (use of shielded cables or metallic cable ducts) are provided, the induced overvoltage U_i is usually negligible and may be disregarded in most cases.

C. Characteristics of the upstream line and of the downstream protected circuit

The characteristics of the upstream line and of the downstream protected circuit strongly influence the value of the probability P_{SPD} that an apparatus, protected by an SPD system, is damaged. If these characteristics are not appropriate to the considered source of damage, it may not be possible to reach values of P_{SPD} equal or better than those related to the required protection level (LPL) obtained from risk assessment procedure [15], even using SPD system with energy withstand very high and very low protection level U_p, among those available on the market.

The main factors invalidating the possibility to reach low values of P_{SPD} are:

1) The voltage drop ΔU on the connections of an SPD. As a rule of art, for all sources of damage, the length l_c of connection leads should be $l_c \leq 0{,}5$ m;

2) The overvoltage U_i induced by lightning current in the protected circuit. To reduce Ui is needed to reduce the induced loop area of the protected circuit. As a rule of art the following condition should be fulfilled for unshielded protected circuit of length up to 100 m:

− $w \cdot k_c / d \leq 0{,}0025$, for source S1;

− $w \cdot l / U_w \leq 3$, for source S2;

− $w \leq 0{,}005$, for source S3;

where, with the same notations of the international standard [15],

− w is the width of protected circuit;

− l is the length of protected circuit;

− k_c is the current partitioning coefficient;

− d is the distance of circuit from inducing current.

This condition is fulfilled by using:

− circuit routing with PE and phase conductors in the same cable;

− screened circuits or laying in a closed metallic conduit.

3) The length L and the number n’ of conductors of the considered line. The electrical stress on the SPD system decrease with increasing of the number n’ of line conductors; the value of P_{SPD}, related to source S3, decreases with increasing the line length L. As a rule of art the following condition should be fulfilled for the line, if a SPD system type S/L is used:

− $n \cdot n' \geq 120$, for source S1, being n the number of incoming services into the structure;

− $L \geq 1000$ m, for source S3.

In conclusion, as discussed in [16] an SPD system type SL or type LL is generally to be used for sources S1 and S3. In fact, due to high values of ΔU, even if overvoltage U_i induced in the circuit is negligible, the distance between SPD1 and apparatus (or the value of U_p) should be kept so low that practically in all cases installation of a downstream SPD2 is required if low values of P_{SPD} are to be achieved.

V. Probability P_{SPD} that an SPD System Fails

As demonstrated in [12], the probability P_{SPD} that an overvoltage will damage an apparatus protected by an SPD system depends on the type of SPD system considered.

A. SPD system S/L type

In S/L SPD system the probability P_{SPD} is to be evaluated as the probability that both condition a) and condition b) will occur.

The probability P_{SPD} is given by:

$$P_{SPD} = 1 - (1 - P_{SPDQ}) \cdot (1 - P_{SPDU}) \qquad (6)$$

being:

− P_{SPDQ} is the probability that the value of Q_{SPD}, relevant to positive and negative first strokes, exceeds Q_{imp} or Q_{max} for SPD class I or class II test respectively;

− P_{SPDU} is the probability that the value of U_{SPD} relevant to the current I_{SPD}, exceeds the required protection level U_{pr}, it is the probability that, for the subsequent stroke of negative flashes, I_{SPD} exceed the current I_{pr} relevant to the required protection level U_{pr}.

B. SPD system SL or LL type

For these two types of SPD systems:

1) For condition a), P_{SPDQ} is the maximum value between the two probabilities P_{SPD1Q} and P_{SPD2Q}, relevant to SPD1 and SPD2 in series, i.e. P_{SPDQ} = max (P_{SPD1Q}; P_{SPD2Q}). If SPD2 is energetically coordinated with SPD1, P_{SPD1Q} only is to be taken into account;

2) For condition b), SPD1 is shadowed by the presence of the SPD2, so that the probability P_{SPD1U} can be disregarded.

The probability P_{SPD} relevant to type SL or LL SPD system can be obtained by:

$$P_{SPD} = 1 - (1 - P_{SPD1Q}) \cdot (1 - P_{SPD2U}) \qquad (7)$$

VI. Procedure for Selection of the SPD System According to the Required Probability P_{SPD}

For evaluation of probability P_{SPD}, the current I_{SPD} expected at installation point of SPD and the associated charge Q_{SPD} are needed. The current I_{SPD} and the associated charge Q_{SPD} expected at installation point of SPD depend on many factors, the most important of which are:

− the installation point of SPD (SPD1 or SPD2);

− the source of damage (S1,S2,S3 or S4);

− the amplitude and waveform of lightning current.

Moreover I_{SPD} and Q_{SPD} depend, for SPD1, on:

− the characteristics of line where SPD1 is installed;

− the conventional impedance of the earth arrangement (Z);

− the connected external services entering the structure;

and for SPD2, on:

− the characteristics of circuit where SPD2 is installed;

− the type of SPD1 (switching or limiting);

− the location of the circuit with respect to inducing lightning current.

A. Evaluation of probability P_{SPD} of an SPD system

The evaluation of probability P_{SPD} of an SPD system to reduce the frequency of damage of the apparatus, is a complicated matter because the probability P_{SPD} depends on the rated current I_n and I_{imp} of SPD in front of the expected current I_{exp} (and the related charge Q_{exp}) at the installation point; as I_{exp} (and Q_{exp}) changes with the source of damage the probability P_{SPD} of a SPD system changes with the source of damage.

Evaluation of P_{SPD} may be performed only if the voltage-current characteristic of SPD is available and the characteristics of the upstream line and of the downstream protected circuit are known.

For each source of damage (S1, S2, S3, S4), the current I_{SPD} expected at installation point of SPD and the associated charge Q_{SPD}, may in practice be evaluated by means of simulation tools, such as, for example, transient software EMTP-RV.

Once the the current I_{SPD} and the associated charge Q_{SPD} have been assessed for each SPD of SPD system, then it is possible to determine the probability P_{SPD} of the SPD system to reduce the frequency of damage of apparatus. Because of the large number of parameters involved, the use of special software may be helpful.

B. Selection of an SPD system with a given P_{SPD}

Even more complicated is the selection of a SPD system able to protect apparatus with a given probability.

To make this selection faster and more simple, plots are needed indicating:

- for SPD1 the values of I_{imp}, and

- for SPD2 the maximum value of U_p at the minimum value of I_n, able to obtain the required probability P_{SPD}.

The plots of I_{imp} and of U_p are drawn on the base of the family of *U*/*I* characteristics relevant to a type of SPD, and should be available:

− for each source of damage (S1, S2, S3, S4);

− for each type of SPD system (S/L, SL, LL);

− for typical circuits SPD1-SPD2 and SPD2-apparatus, according to the conditions reported in Section IV.C.

It is desirable that the plots of I_{imp} and of U_p as function of required probability could be provided by SPD manufacturer.

As an example, plots of I_{imp} and of U_p for a type of SL SPD system , selected to reduce the damage due to sources S1 and S3, are reported in Fig. 2 to 5; in such example a typical upstream line and downstream protected circuit complying with the requirements of Section IV.C, have been considered as follows:

− power line: aerial; length L = 500 m, 10 poles with conventional earth impedance Z_p = 50 Ω; number of line conductors n' = 2; U_w = 15 kV;

− structure: conventional earth impedance Z = 10 Ω; number of connected services n = 1; Lightning Protection System (LPS): k_c = 0,5; d = 1 m;

− circuit SPD1-SPD2: length l_{12} = 100 m; width w_{12} = 0,005 m (circuit conductors in the same cable)'

− circuit SPD2-apparatus: length l_1 = 50 m; width w_{2a} = 0,005 m;

− SPD: system SL; length of connection leads l_c = 0,5 m; SPD2 type *X* whose *U*/*I* characteristic is reported in Fig. 1.

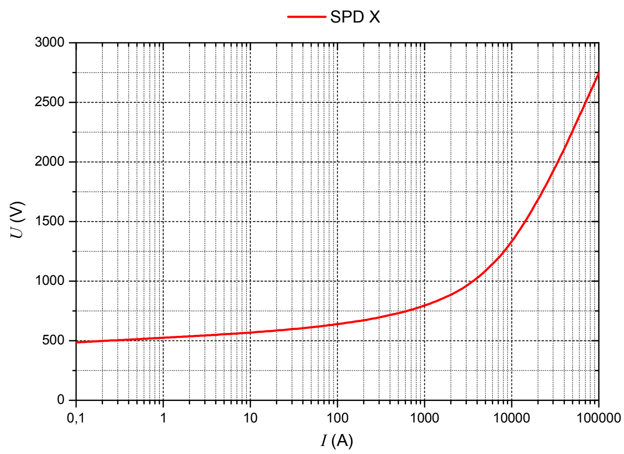

Fig. 1. Voltage-current characteristic of SPD type X.

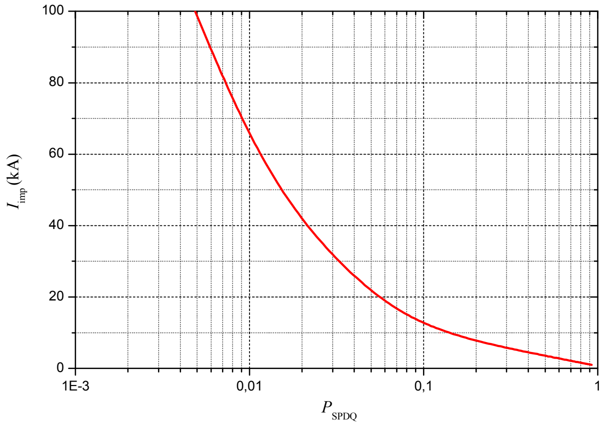

Fig. 2. Source S1 - SL SPD system – Impulse current I_{imp} of SPD class I test as function of probability P_{SPDQ}.

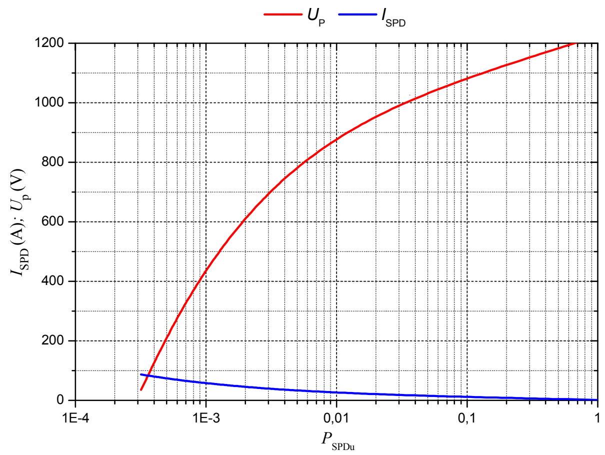

Fig. 3. Source S1–SL SPD system – Values of protection level U_p and of I_n as function of probability P_{SPDU}; SPD2 type *X* is adopted.

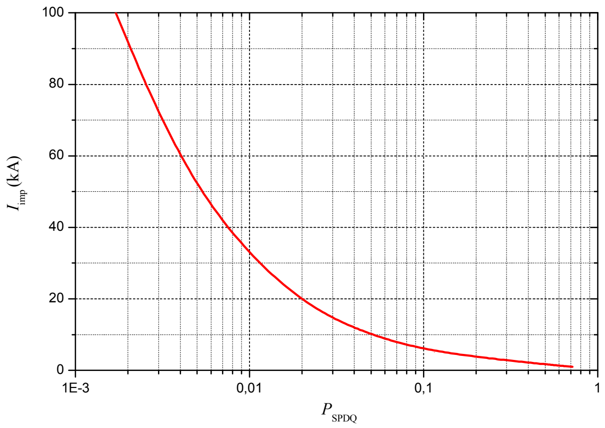

Fig. 4. Source S3 - SL SPD system - Impulse current I_{imp} of SPD class I test as function of probability P_{SPDQ}.

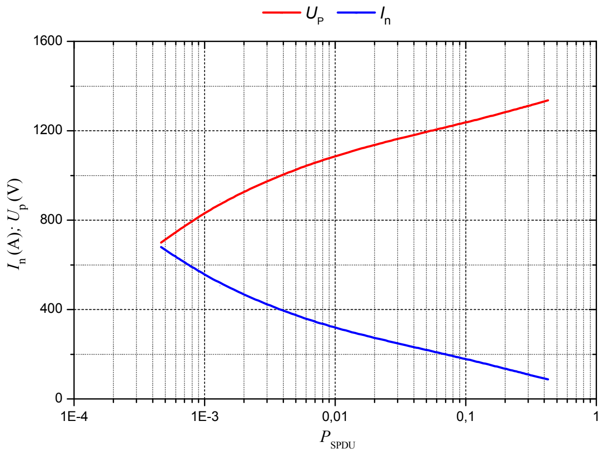

Fig. 5. Source S3 - SL SPD system - Values of protection level U_p and of I_n as function of probability P_{SPDU}; SPD2 type *X* is adopted.

Once the plots of I_{imp} and of U_p are available, the procedure for selection of an SPD system able to protect apparatus with a given probability may be summarized as follows:

1) SPD system type S/L:

- get the needed value of probability $P_{SPD} = 1 – (1 - P_{SPD1Q}) \cdot (1 - P_{SPD1U})$ relevant to SPD system to be installed in order to reduce the frequency of damage to the required value.

- share the probability P_{SPD} among P_{SPD1Q} and P_{SPD1U} so that value of required P_{SPD} be retained;

- apply to plots of I_{imp} and of U_p, relevant to the considered source of damage;

- from the plot of I_{imp} select SPD1 class I with I_{imp} corresponding to the required P_{SPD1Q};

- among the SPDs with the selected I_{imp}, select one that has U_p not higher than those reported in the plot of U_p, at a current I_n not lower than those reported in U_p plot relevant to the required P_{SPD1U};

- the SPD system has been selected and dimensioned according to the required P_{SPD}.

2) SPD system type SL or type LL:

- get the needed value of probability $P_{SPD} = 1 – (1 - P_{SPD1Q}) \cdot (1 - P_{SPD2U})$ relevant to SPD system to be installed in order to reduce the frequency of damage to the required value;

- share the probability P_{SPD} among P_{SPD1Q} and P_{SPD2U} so that value of required P_{SPD} be retained;

- apply to plots of I_{imp} and of U_p, relevant to the considered source of damage;

- from the plot of I_{imp} select SPD1 class I with I_{imp} corresponding to the required P_{SPD1Q};

- among the SPDs energy-coordinated with the SPD1, select a SPD2 that has U_p not higher than the value reported in the plot of U_p, at a current I_n not lower than those reported in the U_p plot relevant to the required P_{SPD2U};

- the SPD system has been selected and dimensioned according to the required P_{SPD}.

This procedure can be used by the designers of electrical systems to select a proper SPD system able to reduce the frequency of damage of the equipment to be protected, at levels no higher than those required.

VII. Conclusions

A procedure is proposed suitable:

- to evaluate the probability P_{SPD} of a given SPD system to reduce the frequency of damage of the apparatus within a structure, and vice versa;

- to solve the designing problem of the selection of a SPD system able to protect apparatus with a given probability.

The evaluation of probability P_{SPD} of an SPD system to reduce the frequency of damage of the apparatus, is a complicated matter because the probability P_{SPD} depends on the rated current I_n and I_{imp} of SPD in front of the expected current I_{exp} (and the related charge Q_{exp}) at the installation point; as I_{exp} (and Q_{exp}) changes with the source of damage the probability P_{SPD} of a SPD system changes with the source of damage.

Evaluation of P_{SPD} may be performed only if the voltage-current characteristic of SPD is available and the characteristics of the upstream line and of the downstream protected circuit are known.

For each source of damage (S1, S2, S3, S4), the current I_{SPD} expected at installation point of SPD and the associated charge Q_{SPD}, may in practice be evaluated by means of simulation tools, such as, for example, transient software EMTP-RV.

Once the current I_{SPD} and the associated charge Q_{SPD} have been assessed for each SPD of SPD system, then it is possible to determine the probability P_{SPD} of the SPD system to reduce the frequency of damage of the apparatus. Because of the large number of parameters involved, the use of special software may be helpful.

This procedure can be used by the designers of electrical systems to assess whether the proposed SPD system is able to reduce the frequency of damage of the equipment to be protected, at levels not higher than those required, or to identify which SPD system, and / or changes to the circuits, are necessary to achieve the objective. This can also be useful for providers of SPD called on to give advice or answers to specific questions asked by their customers and installers. Finally, using this procedure, the manufacturers and suppliers of the SPD may provide in the data sheets of their products information on the most suitable circuit conditions for the use of a given SPD system and on effectiveness so obtainable from these systems expressed in terms of P_{SPD}.

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